On the planning of British aircraft production for the Second World War and reference to James Connolly

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Abstract

A continuous, if at times faltering, path of policy and practice in the procurement of British military aircraft is traced through the years up to and during the Second World War. The focus over the latter part of this period is on the development of procedures for the planning of production programmes within the relevant Government departments, and the growing coordination of that with the corresponding evolution of processes in the manufacturing industry. Though repeatedly threatened by constraints at home and world events, this collaboration produced a robust system of production that at its peak in 1944 employed nearly two million people and delivered more than 2,500 aircraft a month to the Services.

Woven into this account are some details of planning methods used in the Ministry of Aircraft Production, from a bequest of papers of J V Connolly, made recently to the National Aerospace Library, Farnborough.

1 Introduction

1.1 J V Connolly

The donation by his daughter of papers from the estate of James Valentine Connolly to the National Aerospace Library form the occasion for this study (1). These relate mainly to his work on the planning of aircraft production in Britain during the Second World War (WW2) (2).

Born in Sydney Australia in 1907, Connolly showed an early interest in aviation. At the age of 16 he began a long correspondence about commercial air services with C G Grey, editor of *The Aeroplane* magazine in London, and at 18 he gained his pilot's wings at the Royal Australian Air Force base at Mt Cook (3). While reading Engineering at Sydney University, he served as a pilot with the Australian Citizen Air Force and led a student team in the design, construction and flight testing of a training glider. An Australian engineering journal later published details from a dissertation he had written on the design for an advanced fighter aircraft with stressed-skin construction. This came to the notice of Sydney Camm, Chief Designer of H G Hawker Engineering at Kingston, leading to correspondence between them, in which Camm suggested that he should come to Britain.

Connolly first gained experience with the Tugan Aircraft Company in Australia, and also joined the Australasian Branch of the Royal Aeronautical Society (RAeS), becoming its Secretary in 1930, until in 1935 he worked his passage to Britain on a small steamer. There he was taken on as a senior stressman at Hawker Aircraft Ltd, contributing to the design of the Hurricane.

A year later he moved to the British Aircraft Manufacturing Co at Hanworth to work with George Handasyde, who with H P Martin had built their first aeroplane in 1908 and formed the company that was to become Martinsyde at Brooklands in 1915. Connolly had been recommended by Camm, who had worked in the drawing office there himself during The Great War (later World War One, WW1). At Hanworth, he assisted with the design of the Eagle and Double Eagle aircraft, the latter a twin-engine 6-seat cabin monoplane with a high-mounted cantilever wing.

Connolly entered public service in 1937, when he joined the Air Ministry's Accident Investigation Branch. A year later he moved to its newly-formed Air Registration Board as technical assistant to Dr Harold Roxbee Cox. Soon after the outbreak of World War Two they were both redirected to the Royal Aircraft Establishment (RAE) at Farnborough. His involvement in aircraft production began on his subsequent transfer to the Directorate of Statistics and Production at the Ministry of Aircraft Production (MAP).

1.2 The Background

The MAP was set up in 1940 to take over from the Air Ministry the responsibilities for planning the programme of wartime aircraft procurement and promoting the industrial capability required for its fulfilment.

In the Battle of Britain of that year, a sustained German assault failed in its aim to secure air superiority and was ended after 3½ months, frustrated by British ground and air forces operating as an integrated air defence system. Facing superior forces, the fighter aircrew of the RAF suffered heavy losses, but deliveries of new and repaired machines to their reserves ensured that by the end of the Battle its fighter strength was greater than it had been at the beginning [(4)]. Then over the next few years, the British industry built up the rate of delivery of all types of aircraft to the Services to more than 2,500 machines a month.

That outstanding achievement was subsequently reported in the volumes of the official History of the Second World War (War Production Series). These works are lengthy and very detailed - for example, Sir Michael Postan's contribution to the series, though comprising 500 pages dense with information, was presented as 'of an introductory character' [(5)]. As they had to cover the production of munitions for all purposes, it is necessary to search them for material on a particular service. However, Ritchie argued that they were necessarily incomplete, citing two grounds **(6)**. Firstly, they had been written before the government papers of the period became available at the Public Record Office (PRO) - later The National Archives (TNA). Although the frontispiece of these histories states that the authors had been given 'free access to official documents', those perhaps did not include the letters and memoranda on which Ritchie and other later writers could draw to obtain a more rounded view. Secondly, the procurement of aircraft on a large scale was an advanced and complex engineering enterprise, which to be understood fully required a familiarity with the technologies of aviation and manufacture that few historians were likely to possess.

For most of the period covered here, orders for aircraft for the RAF and naval aviation were based on the assessment of operational requirements by the Air Ministry and the Admiralty, mediated by their perceptions of progress in aviation, engine technology and air weaponry, and of relevant international events and political realities at home. These interwoven topics have been widely reviewed and today there is an extensive literature on them. And so only a necessary outline of events is included here, to follow the thread of the planning and organisational elements of aircraft production, an important aspect which seems to be the least well known.

When the focus is the production of aircraft and the planning for that, it is instructive to note first the extent to which actions taken in WW2 had their origins in corresponding ones made to deal with similar situations in the Great War (WW1). After the war the manufacture of military aircraft fell immediately to very low levels and remained so for some years. And so only a selective account of events following WW1 is included, mainly to show a thread of continuity with the restoration of mass production that became necessary again during the 1930s.

The review covers World War 1 and the 1920s in section 2, the 1930s and the preparation for war in section 3, and World War 2 in sections 4 to 8, of which section 6 focuses on procurement from the United States. Section 9 gives a more general review of production planning methods and section 10 summarises how these evolved through interactions between government departments and the British aircraft industry, continuing throughout this period.

2 World War 1 and the 1920s

2.1 Patterns set for the future

The introduction of military aviation in Britain took place over a very short period of time. The first flight of Cody's British Army Aeroplane No1 came late in 1908 (7), but already by 1912 the War Office had formed the Royal Flying Corps (RFC) and aircraft took part in the Army's summer manoeuvres on Salisbury Plain (8). The outbreak of the Great War took place only two years later. For operations in that the RFC was joined by the Royal Naval Air Service (RNAS), administered by the Admiralty. But the wide range of roles that aircraft would come to fill in wartime and the huge scale on which they would have to be produced for these could not have been anticipated.

Before the war, aircraft for military use were purchased after testing of a prototype, which had been offered for evaluation after being designed and built by the manufacturer as a private venture. Few aircraft had been built in any quantity previously, and firms were small and without experience in production engineering. After the war began and large orders were being placed output could increase only slowly. Several important actions taken at that time to speed up aircraft production were to reappear in WW2. These include the first co-operative arrangement for engineering companies organised in 1915 by the engineers G & J Weir of Clydeside, in which parts were produced by a number of sub-contractors for final assembly at the parent firm. By use of dispersed manufacture a much greater output became possible and the practice was adopted elsewhere across Britain.

William Douglas Weir (later Viscount Weir of Eastwood) of the Company was one of many who provide links between corresponding activities in the two World Wars. In 1917 he was appointed Controller of Aeronautical Supplies at the Ministry of Munitions and shortly afterwards became Secretary of State for Air. He held several official appointments in the inter-war years and was a special advisor at the Air Ministry from 1935-38, before being a Director-General at the Ministry of Supply during WW2 (9).

Many aero-engines were obtained from France throughout WW1, but they were also built under licence, together with others of British design. The expertise of firms in the motor industry was quickly brought to bear in this field, benefiting from their acquaintance with the machine tools and techniques of mass production already known at that time, an arrangement also adopted in the approach to WW2.

From 1915 the Ministry of Munitions operated a scheme of National Factory construction, with public funding, to increase capacity in other areas of arms production. When by 1917 provision of aircraft and engines had become too great an enterprise for the Army to manage, this was taken over by that Ministry, which added four national aircraft factories to its inventory. In these and their own premises, motor and other engineering firms were contracted to build airframes to the designs of aircraft companies and the Royal Aircraft Factory at Farnborough (see Figure 1).

Output was supplemented by a number of Aircraft Repair Depots, where damaged aircraft were restored to use, incorporating spare parts and components from stores and others recovered from airframes that were beyond repair. Most of these actions were to be revived when the country was again at war twenty years later.

Figure 1 Aircraft production in World War 1

Top: Wings awaiting covering at Graham White Aviation Co. Ltd., Hendon

Bottom: Royal Aircraft Factory SE5a fighters built under licence at the Austin Motor Co. Ltd. (Philip Jarrett collection)

Through them and other factors, the number of aircraft delivered to the Services by British constructors rose to nearly 2,700 a month by 1918. The total output has been given variously, but would most likely have reached a total of more than 58,000 machines over the four years of the conflict [10, 11]. To build that number of aircraft required techniques to be devised for the sequential construction of identical airframes and engines on a large scale. However, Connolly was to write subsequently that 'little emerged during the First World War which can be regarded as any advance by the aircraft industry in the field of production technology' [12]. There had been a great evolution of the concept of the military aeroplane and of the roles it could undertake in warfare, but although there were some consequential developments in airframe design, these did not much alter the basic construction of wooden frameworks skinned with doped fabrics. The requirements for strength and stiffness were met throughout by the use of girder assemblies, for the main structural elements of fuselage frames, wing spars and ribs.

Manufacturers were used to working with timber, and there was an abundance of skills in that from carpenters, joiners and others, including those in the furniture industry, some of whom already had experience of making products in quantity. Output was increased mainly through the provision of greater space, a larger workforce and more intensive working, rather than by any basic changes in technology.

The use of metals evolved outwards from the 'strongbox' of the forward and mid-fuselage, the basic part of the airframe that came under greater forces as the speed and manoeuvrability of aircraft increased. Metal fittings had always been used in the wire bracing and control systems, and were now applied more widely to strengthen joints between timber components. The high strength-to-weight ratio of selected timbers was hard to match, though by the end of the war, fuselage frameworks were being made with steel members, which were less vulnerable to combat damage and quicker to build. On the outside, steel and some light alloy sheet was first noticeable in the use for engine cowlings, and by the later stages of the war the front part of the fuselage of many fighters had metal skins, at least back to the cockpit. The use of metals was somewhat more extensive in the construction of the larger bombers, though these began to emerge only towards the end of the war, and did not reach manufacture on a large scale.

Changes to tooling needed for this limited use could not be said to be revolutionary, though the introduction of machine tools and much greater use of jigs and fixtures was required to make accurate parts and to assemble them into sections of increasing size up to the point of final build. The principle of interchangeability of parts between aircraft of the same type and mark, with a cadre of inspectors to oversee that, came into being at this time. An important part in the expansion of the industry was the influx of workers required to bring the pace of deliveries up to the rate demanded by the Services, the workforce reaching 268,000 overall by the end of 1918 (13). Most of those came with no previous relevant experience, requiring programmes to be developed for systematic training on a scale never needed previously. They now included a high proportion of women, contributing to a fundamental change to the nature of society.

As according to Connolly there had been little advance in production technology, nor had there been much understanding at any level of the need for forward planning and organisational procedures if the resources, human and material, were to be used efficiently. The use of subcontracting was one example of an initiative imported from other parts of industry rather than an implementation of central government policy.

A review in 1917, led by General Jan Smuts, foresaw the increasing strategic significance that air power would have in the future. Its recommendation that Britain should form an independent force of equal standing with the Army and Navy to project that power led to the foundation of the Royal Air Force (RAF) in 1918, by a merger of the RFC and RNAS. An Air Ministry was formed to administer it, overseen by the Air Council, chaired by the Secretary of State for Air in the Government. There was, however, little appreciation of the requirements of an industry to sustain the new force.

Alfred Gollin, an American scholar of European history, used the phrase 'no longer an island' for the recognition by some in Britain of the implications for their homeland of the coming of manned flight, and he went on to review reactions of the public and Government to the development of military air power prior to the Great War (14). The fears of the populace were shown to be all too real in the later years of that war. Casualties and damage through German bombing of London and south east towns, at first by airships and then by large bombers, were extensive and disturbing (15). By that time, Germany could not muster large resources for this activity, but with quite small numbers of aircraft the raids that were mounted were sufficient to cause widespread alarm and a general lowering of morale in the areas attacked. The damage and casualties were widely reported and had a powerful influence on public opinion, already aroused by the predictions made before the war in books and films about destruction raining down from the air.

Attempts to deter and destroy the raiding aircraft led to the introduction of the first integrated air defence system, not widely acknowledged subsequently, with components that would be revived and developed in the inter-war period. Reminiscent of those that proved to be decisive at the beginning of WW2, they included "the ring of fighter bases and the air defence zones, the listening stations, barrage balloon screens, mobile and static anti-aircraft batteries, LADA (the London Air Defence Area), the communications net, even the Operations Room with its giant map table manned by staff plotting the movements of attacking and defending aircraft with the aid of counters and wooden rakes" (15). An operator claimed that from the time that an aircraft was first observed to when the counter for it appeared on the map was 'rarely more than half a minute'. This system achieved only limited destruction of bombers in WW1, but the evidence of resolute opposition that it provided had a significant effect on the morale of their crews, causing a high proportion of raiders to turn back early or to jettison their bombs away from the city.

2.2 The 1920s

At the end of the Great War there was a firm resolve that it was to be 'the war to end all wars', and the Services and munitions industry were rapidly and hugely cut down. The cost of the conflict, in human and material terms, had been such that in Britain it was followed by more than a decade of national retrenchment and economic stringency. But successive governments had somehow to balance their decisions on finance to reconcile the strong public antipathy to anything military with the continuing perspective that Britain and its Empire was a world power, with international obligations to be honoured.

The basis adopted for policy planning was the assumption that the country would not be involved in another significant armed conflict over the next ten years. The size of the RAF had been reduced greatly after the war, and funding provided for it was small. Air Chief Marshal Sir Hugh Trenchard, as Chief of the Air Staff (CAS) from 1919 to 1929, concentrated on putting in place the foundations and organisational structure that would preserve his vision for the Force in the long term. This was as an independent Third Service, small but staffed with highly trained professional officers and men, with a Reserve that could enable it to be expanded quickly in an emergency. He consistently argued the case for maintaining a force of bomber aircraft, foreseeing a future war as a contest in which 'the nation that would stand being bombed the longest would win in the end' (9).

Responsibility for administering Treasury funding for air operations was passed to the Air Ministry in 1920, but the allocations remained minimal. The supply of new aircraft to the RAF had fallen in its first years to a level that was barely sufficient to cover losses through retirement and accidents, so the force had to be organised around obsolete WW1 types that had been kept in service, like the Bristol F.2B 'Fighter', a versatile machine shown in Figure 2, that was popular with aircrew.

One area for which equipment at squadron level would have to be maintained was the administration of the Middle Eastern regions that had been mandated to Britain by the League of Nations in 1923. For their largely desert areas, it had been decided to exercise 'control without occupation', involving extensive policing from the air, and some new types were introduced in that sector (16). The Hawker Hart, the two-seat light day-bomber shown in Figure 2, was to serve this purpose well and was followed by several successful derivatives. It could be considered to be an intermediate type, required by its development specification 12/26 to have an all-metal structure, though the lifting surfaces and rear fuselage were still fabric-covered. With the Rolls-Royce Kestrel engine, it sold well overseas and others were built under licence.

Figure 2 Progress in design

Left: Bristol F.2B Fighter, 2 seat WW1 type which remained in service until 1932 Right: Hawker Hart light day bomber, entered service in 1930

The Air Ministry took a long view on procurement from the beginning, and in general can be said to have used its limited resources shrewdly. Though a new type would still be ordered only after rigorous testing of a prototype, the Ministry began reviewing the operational requirements for the service and issuing specifications for aircraft that would be appropriate for them. Orders for new types and derivatives were rationed around the few aircraft companies that remained in business. These comprised larger firms that had been founded before the war, plus some new ventures, mainly started up by leading figures from other companies that had gone into voluntary liquidation at the end of the war. For example, production of the Hart under specification 9/29 was contracted to Armstrong Whitworth, Gloster and Vickers as well as to the parent company, spreading experience with metal construction. But this was a lean time for the industry. Occasional production was not economical, so these companies were often a part of a larger engineering group. British aircraft generally sold well to forces in Dominion countries and others overseas, and some support was given by the nascent demand for new civil aircraft and diversification into non-aviation manufactures. The Ministry also sought to provide for the advancement of aviation technology by the purchase of experimental machines, though rarely with more than two examples. In this quite basic process there could be no call for the development of facilities or planning systems for aircraft production of any substantial scale.

Looking forward, the Ministry devised a series of 'Schemes', setting out successive views of the needs for new aircraft types by number and operational role [(17)]. These, labelled alphabetically, would eventually reach Scheme M, but although they aimed to be realistic and supported by reasoned argument, they had to take their place with other financial demands which arrived at the Estimates of the Treasury, and would not in practise be matched by funding allocations.

It was generally reckoned subsequently that by working to a rolling 10-year rule, successive governments had avoided making any provision for defence of the homeland against attack from the air. But in 1923 Parliament agreed to establish the 'Parity' principle that defined an enduring role for the RAF and acknowledged the scale of the resources it would need. This principle required it to grow and then maintain a Home Defence force, 'of sufficient strength to protect us against air attack by the strongest Air Force within striking distance of this country' (9, 18). At the time, that would have been the French, and it was concluded by comparison that the strength should grow to 52 squadrons, with 550 front-line aircraft. From its beginning, the Air Staff's interpretation of the nature of home defence for Britain was that it should rely principally on a powerful strategic force to act as a deterrent to air attack. Accordingly, bomber aircraft had always been included in their planning, and in their view many of those new squadrons would need to be equipped with bombers, some large enough to threaten devastating consequences to any potential attacker. It had become accepted that air warfare would not only involve attacking an enemy's forces, but would primarily be aimed at its industry and infrastructure and would inevitably involve the civilian population.

There would also be a defined role for fighter defence as a further component of deterrence. A joint committee of the Air Ministry and the Army (the Steel-Bartholomew Committee) made the first recommendations for a permanent air defence structure for Britain in 1924. An arrangement similar to that hastily conceived in WW1 was now revived, and supplemented by a chain of coastal sound-locators and observation posts on which the Observer Corps was founded. In 1925 an Air Defence of Great Britain Command (ADGB) was formed, to provide and operate the network as an integrated whole.

For the core of this system, Air Ministry Scheme C of 1928 made a case for the delivery of 3,800 aircraft to the RAF over a period of two years, of which a large component would be bombers. A further concept, that appeared around this time and would be revised regularly later, looked beyond the immediate requirements, to define what was termed War Potential (5). This was a general assessment of the resources that would be needed by the Services in the event of a prolonged war. In a necessarily hypothetical assessment, it was concluded that capacity would be required for production of aircraft rising to 2,000 a month, and to be sustained at that level. Numerically, this was no more than had been achieved in the Great War, but the implications of producing that number with the growing complexity of aircraft design had not then been considered seriously.

The difference between the two planning concepts now established for British air policy should be emphasised (6). Parity defined the level of production required in peacetime for its strength in the air to match that of the most powerful foreign force within range. War Potential was not a reserve level of production to be held in readiness for war, but an enhanced production programme that would be implemented if war seemed imminent. Under the urgency of wartime circumstances, it would provide for the output to be raised to a level much higher than the peacetime Parity programme, though it was accepted that it would take perhaps two years for it to develop sufficiently to reach the planned peak figure. The nation's stance would not be able to complete a move from the defensive to the offensive until the War Potential was fully operative.

Aviation journals were having an increasing voice, and quoted the Secretary of State for Air, who stated that by the end of 1928 the use of wood in aircraft would be entirely displaced by metals, except in the case of a few training types (19). But although the Air Estimates were said also to be sufficient for the complete re-equipment of the RAF by April 1930, it soon became apparent that neither of those objectives would be achieved. This was not only because in reality the allocated finances would not match the Air Ministry's proposals, but from another factor that was to assume primary importance later. It was found that the industry would not have been able in peacetime to build up the capability in either design or manufacture required to implement Scheme C within two years. Its staff in both sectors lacked the expertise to effect the changes in practice required, and it did not have the work-space, equipment and tooling, materials supply chain, trained workshop and inspection personnel, nor the administrative systems required to produce at that level. The Air Ministry now began to see that future schemes could not be based on perceived operational needs alone, but would require assessments to be made of what it might be practicable for the industry to produce.

In the last years of the 1920s, the total delivery of aircraft of all types to the RAF averaged around 500 a year. After replacements for accidents and retirement of WW1 types that still remained in service, perhaps 50 could be allocated to the formation of new units. Postan noted that a decade after Scheme C the Home Defence force had reached only 42 squadrons [(5)].

It is fair to remember however that the authorities faced the greater distraction of the effects of the Great Depression that began to afflict the British economy following the crash of the US stock market in 1929.

3. Developments in the 1930s

3.1 The Government stance.

The 1930s were to be a decade of historic changes, driven by the growing evidence that there were again in Europe and the Far East nations for which aggressive force of arms was to be a central instrument of policy. Air power arising in Germany caused considerable alarm and calls for Britain to respond. Stanley Baldwin, not then Prime Minister, though a member of the Government, warned in a speech to Parliament in 1932 that every effort should be made to avert a possible coming conflict, in which attack of the homeland from the air would be a major element. A vigorous doctrine of 'homeland defence' should be adopted, but people should realise that 'the bomber will always get through'. He added candidly that, to be effective, a threat of retaliation by Britain would have to be backed by a willingness to 'kill more women and children more quickly than the enemy' [(20)].

The assumption for planning purposes that there would be no significant conflict for ten years was dropped, but financial provisions for the RAF still provided little for expansion - in fact no funding for forming new squadrons was provided in 1932 and 1933 [(5)]. Continued rationing around the manufacturers required that any order would be for a very limited number of machines, still providing no incentive for the consideration of methods for planning and production on any significant scale.

Governments were reluctant to implement the Parity concept fully while discussions continued at the international Disarmament Conference in Geneva, but hope faded when the Conference was abandoned after Germany and Japan had withdrawn. They also resigned from the League of Nations, and the components of what became the Axis powers fell into place. In 1936, the ground that had been lost by Britain became more starkly apparent, with the beginning of the Spanish Civil War. Germany and Italy gave military support to Franco's Nationalist side, especially through a substantial force of bomber and fighter aircraft. The world's press would now bring to public attention the scale of German rearmament and report the nature of the warfare it was prepared to project from the air, including indiscriminate bombing of undefended civilians. This would show also the operational readiness of the Luftwaffe, the result of its training programmes carried out at secret locations leased in the Soviet Union.

3.2 Aircraft in the 1930s

Widely differing opinions emerged within the Air Ministry on the features required for new aircraft to match developments elsewhere [6, 17]. The types that were eventually ordered were the outcomes of compromise and delay, but some from this period would be in service when WW2 began, having been the subjects of an eventual expansion in productive capacity in the later years of the decade. The numbers of a type being ordered duly rose far beyond any that had previously been made in peacetime, and finally made clear the need for an associated development of a systematic approach to planning.

3.2.1 Public awareness.

Despite a general unwillingness to contemplate another war, in this period public interest in aviation continued to be high, a frequent topic of reports in newspapers and articles in popular magazines. Crowds were attracted by air-racing events, engaged in by enthusiasts wealthy enough to order aircraft from small British specialist firms that were later to feature in significant contributions to production in wartime [21]. The RAF, keen to capitalise on air-mindedness in the country, had held an annual Air Pageant at Hendon from 1922, and with the Air League of the British Empire, instituted the Empire Air Days in 1934. RAF stations were opened to the public, to show the Service 'at its everyday work', the day always ending in a flying display. Public awareness was served also by widely-reported events such as newspaper-sponsored flying challenges, and events like the outright capture of the Schneider Trophy for seaplane racing and the first flight over Mt Everest. Notable world records won by British aircraft in this period included that for speed (407.5mph), altitude (nearly 54,000ft) and distance non-stop (over 7,000 miles). But the machines for these had been designed for specific purposes and research, and could provide only limited information on design methods directly transferable to service aviation and nothing to techniques of series production.

The enthusiasm of the public and the media helped to start a minor boom in investment in aircraft manufacture, continued by the amalgamation of parts of the industry into larger groups and of smaller firms becoming public companies [6]. This provided more stability, but as in other businesses, enlarging and modernising facilities for manufacture always depended on the scale of orders and the prospect of further ones to follow. The monthly journal *Aircraft Engineering* made its appearance in 1929 and became very popular, widely read at all levels across the industry. Its coverage included reviews of aircraft exhibited at the Paris Air Shows, design features of other civil and military types from many countries, new materials for aircraft construction, fabrication and production methods, data sheets for routine design processes and reports of visits to aircraft firms with details of all these aspects, supported by drawings and photographs. Contributions were included on recent research on aspects of aeronautics by staff of universities, the Royal Aircraft Establishment and the National Physical Laboratory (NPL). From 1932 there was a special section on Workshop and Production.

3.2.2 Aircraft design.

In 1929, Prof Bennett Melvill Jones had introduced the concept of an idealised 'Streamline Aeroplane' [22]. This would be one in which the only source of drag had been the inescapable 'skin friction' of its essential aerodynamic surfaces. He showed that compared with that, contemporary aircraft needed engine power from two to four times as great to reach the same maximum speed. It omitted all 'parasitic' drag, and current types still included features such as open cockpits, uncowled engines and fixed undercarriages that contributed to that. For a biplane this was further increased by struts and bracing wires, and more subtly by a reduction in aerodynamic efficiency through the interference of the airflow over each wing by that over the other. It has been claimed that the Air Ministry had a prejudice against monoplane aircraft due to early structural failures with that layout, but that has been refuted by reference to contemporary official documents (17). Some firms were content to continue offering mostly biplane types, with which they now had lengthy experience, but it had been recognised that this pattern left limited room for improvement in performance and most had accepted the need to acquire the necessary expertise to offer monoplanes against specifications expected in the early 1930s (23).

Colin Sinnott acknowledged the difficulties under which the Air Ministry had to plan the ordering of aircraft for the RAF. Virtually from its formation, it "had to take decisions on the aircraft performance characteristics needed to fight an air war at an unknown time, against an unknown enemy, and against a rapidly-changing technical background" (17). Though that was so, it had been allowed to lead to endless discussions that perpetuated indecision. Weir was less forgiving, calling the system 'an evasion of responsibility', that 'may result in a reliable decision, but the march of progress renders the ultimate selection obsolete' (6). But despite the tortuous path of these proceedings, a variety of types reached reality during this period. These were still the result of rationing orders around the firms, helping to keep the industry in being, though it meant that orders remained too small to justify any investment in planning and facility for serial production.

3.2.3 The fighters

As Home Defence took its place in strategic planning, the Air Ministry issued Specification F.7/30, for a 'zone fighter' to intercept bombers approaching from the continent. The name arose from the Aircraft Fighting Zone that had been defined, beginning at about 30 miles inland from the south and east coasts of England. An outer coastal Gun Zone and an inner one to protect the approaches to London were on either side of that, concepts that had been revived from similar arrangements in WW1.

The issue of F.7/30 exposed the inadequacies across the whole system of aircraft procurement. A specification of that time would prescribe quite detailed requirements for basic technical features such as weight, maximum and landing speeds, ground runs on take-off and landing, rate of climb, service and ceiling altitudes, flight duration, armament and others according to the duty. Staff in the Directorates involved often had very differing views on these. It was agreed that the short times of engagement for fighters would require a high rate of fire from gun installations, but there were opposing views on the relative merits of single and multiple fixed guns and moveable turrets, and the use of standard 0.303in ammunition carried in large quantities or 20mm cannon shells containing explosives, which would be individually more damaging, though fewer could be carried. There were other issues, so when a specification was finally arrived at, it was at best a reluctant compromise.

It was also a difficult time of flux for the industry, when designers and constructors were adapting to the fundamental changes of the 'monoplane revolution'. These required a new approach in engineering technology, away from the girder construction in use from the beginning of flight, in which no load-carrying capacity was expected from the fabric covering, to one in which a metal skin carried a high proportion of the loading, both in bending and torsion. The combination of difficulties in the Air Ministry and the industry repeatedly delayed even the competitive trials of prototype designs to F.7/30 until they finally took place in 1935. Yet even after this hiatus, none of the proposals was considered to match the requirements sufficiently for acceptance. And so the stop-gap decision was taken to order the Gloster Gladiator for RAF service, still a biplane type, as shown in Figure 3, but with some modern features such as an enclosed cockpit. The concept of the biplane did not entirely fade out, and all of the combatants in WW2 employed it for some duties.

Figure 3. Gloster Gladiator
The last biplane fighter ordered for the RAF, entered service 1937

Criticism of the manifest inadequacies of the procedures for procurement had been expressed in a prominent editorial for *Aircraft Engineering* in 1934 [24]. It noted that new civil aircraft were being designed and built in nine months, while military types were obsolete before any reached the point of manufacture and delivery. To speed up the process for military types it was suggested that there should be a production and planning department at the Air Ministry and a direct input to the process from the industry - a confidential advisory committee could be set up for this purpose by the Society of British Aircraft Constructors (SBAC), which had been in existence since 1916. Specifications should be shorter and simpler, defining a single specialised duty. Technical requirements should be kept to a minimum, leaving more room for initiative during the design process. To encourage new concepts, there should be more orders for experimental machines, and where a prototype was ordered, manufacturers could also produce a lightweight version to get the quickest possible air experience with the layout, perhaps even one with a wooden structure if that could be built more quickly, and while there were still skilled craftsmen available to work with that material. When a foreign machine showed a recognisable advance on which data were lacking in Britain, a specimen should be purchased, designers from various firms allowed to examine it and their test pilots to fly it. Similar steps were proposed for the aero-engine firms.

Other suggestions were for intervention into the market, to obtain duplication of materials and components suppliers where delivery delays were causing problems, and for distinctive firms to specialise in the design and supply of larger components such as undercarriages. These ideas were generally very sensible, and seem to have been influential, though they were adopted only gradually. Recommendations similar to some of them were still being set out a decade later [25].

The disastrous competition for F.7/30 was followed by F.5/34, a shorter specification concentrating on the daytime interception role. Proposals submitted for this showed that the industry was adapting to the new performance requirements, but developments had been needed in nearly every aspect of design, and again none of them could meet the specification in full.

Stanley Baldwin (then Prime Minister) announced that Germany would now be the nation with which Britain would plan to establish parity in the air [26]. Further specifications were issued, in which F.9/35 led to the ordering of the Boulton Paul Defiant in significant numbers. This was the two-man all-metal monoplane shown in Figure 4, with clean lines, taking advantage of being fitted with the Rolls-Royce Merlin in-line engine, with its low frontal area. It had enough duration in the cruise to mount standing patrols, but its performance was degraded by the extra weight and drag of the 4-gun dorsal gun-turret with which it was armed. An initial order for 87 was placed before the prototype had flown, though it still did not enter service until 1939.

The popular image of the ultimate interceptor fighter of the beginning of WW2 is of a highly-loaded single-seat monoplane of streamlined all-metal stressed-skin construction, with flaps and retractable undercarriage and an enclosed cockpit with oxygen supply and radio. It would have a high rate of climb and maximum speed, to get into position in time to intercept bombers and escorts at their likely altitudes, to be highly manoeuvrable and armed with multiple forward-firing machine guns to obtain a sufficient hit-rate to disable targets in very brief periods of engagement. Aircraft like that did arrive eventually, though not by the procedures outlined above.

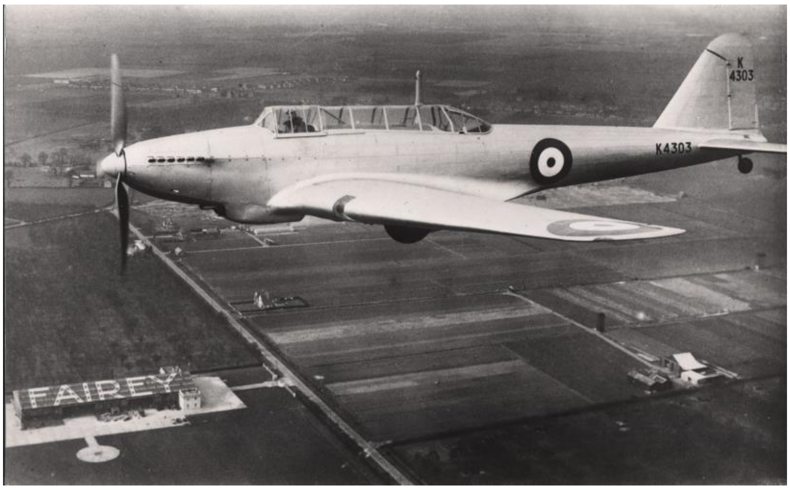

Figure 4. Types with rear armament

Top: Fairey Battle light bomber, entered service 1937
Bottom: Boulton Paul Defiant turret fighter, entered service 1939

Increasing interaction between the Air Ministry and the aircraft companies now included short-cut support being given directly to firms like Hawker and Supermarine, which were both working on fighters as private ventures. These had been stimulated initially by F.7/30, but now were aimed at maximum performance while incorporating additional features from later specifications. With this continued support, these aircraft were finally developed to become the Hurricane and Spitfire, shown in Figure 5, for which individual specifications F.36/34 and F.37/34 were issued. There had been further direct interaction between the Ministry and Rolls-Royce over development of the Merlin engine, also initially a private venture. Prototypes of the two machines first flew in November 1935 and March 1936 respectively. The urgency now perceived for these high-performance fighters was enough for first production orders for 600 Hurricanes and 310 Spitfires to be placed on the same day in June 1936. The first Hurricanes were still fabric-covered, and the rear fuselage continued with that after a metal stressed-skin wing was provided for it from April 1939. With greater attention to the requirements of manufacture, the Hurricane was easier to build in quantity and to repair than the Spitfire.

Orders on this higher scale enabled more attention to be given to the requirements of series production. They had become possible following a recommendation of the Committee on Policy and Requirements for a revised aircraft production programme, which became Scheme F in February 1936. This was intended to provide more than 8000 machines of all types over a period of three years. The Air Ministry had argued that this Scheme would be 'much more effective' than the previous one, as it would now include new types of fighter and bomber aircraft that would embody the latest technical advances. It is reckoned to mark the beginning of the rearmament of the RAF prior to WW2 (6).

Difficulties in production on this scale had now to be addressed more purposefully. A new Directorate of Aeronautical Production was established at the Air Ministry in an acknowledgement that it would in future have to take a direct interest in the processes of producing the machines that it ordered.

Figure 5. Single-seat fighters

Top: Hawker Hurricane, entered service 1937
Bottom: Supermarine Spitfire, entered service 1938

3.2.4 The bombers.

The differences at the Air Ministry over the specifications for bombers were no less than for fighters, and there were similarly long delays in reaching production (17). RAF doctrine stressed the strategic role of bombing, which would require penetration into defended airspace. With France seen at first as the potential enemy, a range of 1,000 miles with a bomb-load of 1,000lb was the duty specified, with a cruise speed of 200mph, which with small size would lower the likelihood of interception. The first of the new types that eventually emerged included the single-engine Fairey Battle, shown in Figure 4**.**

Designed to P.27/32, the Battle was conceived as a light bomber replacement for the Hawker Hart. The Fairey concept was a considerable advance for its time, and much was expected of its operational performance, as the first RAF type to use the Merlin engine, together with a de Havilland 3-bladed propeller with 2 pitch settings, adjustable in flight. To maintain a slender form, the 3-man crew was seated in line under a long canopy. The third member was nominally the radio operator, but by turning aft, he could fire a manually-operated gun through an aperture at the rear. There was also one fixed forward-firing gun in the starboard wing. An initial order for 36 was placed in 1933, but when a larger one was placed in 1935, the notional enemy had become Germany, so although it met the original specification, its range would not then be adequate.

Designed to B.9/32, the larger twin-engine Armstrong Whitworth Whitley, Handley Page Hampden and Vickers-Armstrongs Wellington medium bombers, shown in Figure 6, were more comparable with contemporary German machines. It was a basic belief at the Air Ministry that a bomber must be able to defend itself against fighter attack, so that gun turrets were much in evidence. All these types were still in service when war came, and were actively involved in the early operations, but the Whitley and Hampden were soon overtaken by later designs and only the Wellington had features that enabled it to be continuously developed so as to remain in production throughout the war. One of the successors to these types was a Bristol private venture that became the Blenheim, a military version of the company's 'Britain First', a sponsored twin-engined low-wing monoplane for six passengers, which had shown a maximum speed of over 300mph in 1935. A conversion under B.28/35 included raising the wing to provide room for a bomb-bay and fitting armament that included a dorsal gun-turret, though that lowered the performance to the same range as for the other medium bombers. First deliveries were made in 1937, so that by the beginning of WW2 a dozen squadrons were in service, many at overseas stations, and others were being equipped with a more capable Mk IV version. Together with derivatives, the Beaufort coastal defence torpedo-bomber and Beaufighter ground-attack and night-fighter, this trio of Bristol aircraft made vital contributions in multiple roles in the first years of the war (see Figure 7).

Figure 6. Medium bombers

Top: Armstrong Whitworth Whitley, entered service 1937
Middle: Handley Page Hampden, entered service 1938
Bottom: Vickers Wellington, entered service 1938

A range of 1,000 miles would reach as far as the industrial complex of the Ruhr valley and on to Berlin, but not to a large part of Germany to the east. The emergence of the Axis collaboration meant that targets in Italy would also be relevant. So the strategic aims of the Air Ministry would require heavier bombers, with longer range and much larger bomb loads. There were again opposed opinions on how to provide for these, it being proposed to use the existing standard grass airfields providing only a 500-yard run for take-off and landing. Measures such as enlarging the airfields (though only to 700 yards), and requiring the aircraft to be provided with assisted take-off, by catapult or other means, were repeatedly debated [17].

With compromises finally agreed, specifications were issued for heavy bombers (B.12/36) and for new medium bombers (P.13/36). The operational range for the former had become 2,500 miles, with a ferry range of 3,000 miles for providing support in more distant theatres. Maximum bomb loads were to be 14,000lb. A cruise at 250mph was required at 15,000ft on two-thirds full power, with maximum speed for both types of 275mph. It was required that they should be designed for catapult-assisted take-off, providing an acceleration up to 2.5g. No research or experimentation had been done at the time on the means by which that could be achieved, and it was never adopted in practice.

In fact much of this uncertainty would be overtaken by technical innovations already coming along, which would be incorporated as the increasingly-capable aircraft manufacturers brought forward their proposals. The most significant of these were the use of high-lift devices (particularly flaps) by which landing speed and run of an aircraft could be kept down as cruising speed went up, and the 'constant speed' propeller, that by automatically changing the pitch of the blades allowed an engine to run at its most efficient rotational speed over most of the full range of flight speed, providing the economy that the longer ranges would require.

Substantial changes made before production took place led to a better outcome than might have been expected. Shorts had been invited to submit a proposal for the heavy bomber class and its design was selected for production as the Stirling. As Handley Page worked on its design for a medium bomber, it was realised that with four engines it could form the basis for an

Figure 7. The versatile Bristol trio

Top: Blenheim light bomber, entered service 1937
Middle: Beaufort maritime attack bomber, entered service 1939
Bottom: Beaufighter maritime/ground attack bomber and night-fighter, entered service 1940

aircraft to meet the specification for the heavy bomber, and in due course it became the Halifax. Avro's twin-engine entry was the Manchester, which went into production, but at an early stage it too was to be developed with four engines to become the Lancaster. The Stirling, Halifax and Lancaster, shown together in Figure 8, were late in arriving, but would become the mainstay of the RAF strategic bomber force in WW2.

4 The widening need for planning of production

4.1 The Air Ministry and Industry

The implementation of Scheme F marked a period of rearmament, that would involve wide-ranging developments in the process of aircraft procurement that in peacetime required careful handling by the Government. The progression during the 1930s to the use of light alloy all-metal construction was fitful, but it would ultimately require revolutionary changes throughout supply industries as well as in aircraft manufacture. As rearmament accelerated, these changes would also entail a great expansion in planning, in the firms themselves as well as at the Air Ministry.

Images of aircraft production usually show lines of airframes at the final assembly stage, tending to obscure the huge variety and scope of the prior stages of manufacture of the components that were to be assembled. Vital ancillary elements of the system, that needed to be in place in the second half of the 1930s and continually expanded throughout WW2, require emphasis and are reviewed briefly here. Relevant lessons from WW1 had not been forgotten, and can be traced in several places.

4.1.1 The 'Shadow Factories'.

Along similar lines to those of the National Factories of the Great War, these were substantial new facilities for munitions production that could be organised and brought into being separately from the existing industries in the field and without disturbing their own expansion operations. Now being prepared in peacetime, it was expected that the shadow factories would begin to be brought into use as the extra capacity was needed during rearmament. The majority of the first facilities were for aircraft and aero-engine production. These were to be followed later by others for this sector, forming part of an enormous undertaking, covered extensively in the official histories [27, 28].

Shadow Factories were later blandly described by the Air Ministry as 'somewhat novel enterprises', though the terms of the arrangements for establishing and running them were not exactly modest. Rogers has recently produced a digest of documents in The National Archives concerning the scheme, which detail these arrangements [29]. The entire cost of a shadow factory was to be met from public funds. This covered the purchase of the land, the erection of the buildings and building services, and the provision of all plant and equipment. A management company was appointed, charged with supervising the erection, laying out and equipping of the factory, the provision in due course of the personnel required for administration and the production workforce, obtaining all material and components needed for manufacture and bringing about the production itself, in accordance with specific Air Ministry requirements. No cost for production was borne by the company responsible for the design of the product. All expenditure by the management company was covered by a comprehensive agreement which included a bonus scheme for 'rewarding economic production'. As had been the case in WW1, the first companies to be contracted for this purpose were the larger firms of the motor industry, so as to draw on their experience with the requirements of mass production.

Twelve shadow factories were put in hand in 1936, including two for manufacture of airframes and a consortium of six factories for aero-engines. Two others were for carburettors and one each for propellers and bombs. They were not just to be held in readiness - the guarantee of finance and the energy of the management companies chosen to take them on resulted in some being up and running quickly, and all were in full operation within two years.

Expansion of production capacity was also encouraged in parallel at existing aircraft plants and in new buildings nearby, as needed for the completion of Scheme F. Support for this was given in the form of assurances that further orders would be forthcoming. From the beginning of expansion, there had been concern for the vulnerability of aircraft production to the effects of enemy bombing. South, South-east and Eastern England and two large areas around London and Birmingham had been designated as particularly dangerous locations in this respect. A part of Britain considered to be safer was northwards of a line drawn north-eastwards from the Severn Estuary to a point inland from the coast of Northumberland and then north-westwards through Linlithgow on the Firth of Forth. Regions throughout Britain with high unemployment had been preferred for development support in the inter-war period, but as the war approached, with the call-up for the Services and the expansion of facilities for supply of other military equipment, there was soon competition for labour everywhere, requiring compromise on the official policy for site location.

Figure 8. Heavy bombers

Top: Short Stirling, entered service 1940
Middle: Handley page Halifax, entered service 1940
Bottom: Avro Lancaster, entered service 1942

4.1.2 'A new basic industry'.

William Hornby used this term to describe the facilities needed for the large-scale production of light alloys of aluminium and magnesium, almost exclusively for the aircraft industry [(27)]. Specialist firms for supplying these materials existed in the early 1930s, but a huge expansion would be required as rearmament progressed. Most of the smelting and refining required was encompassed by two firms, but they were to prepare for a greatly increased output, not only directly from ores, but also from the recycling of alloy material recovered from aircraft that had crashed or been withdrawn from service for other reasons.

In the early 1930s, aluminium alloys were supplied mainly in the form of billets to be turned into castings and forgings for aircraft engines. There were many firms with experience of casting throughout Britain, so some were sought out to be trained up for precision casting for aircraft manufacture as that need arose. But the change to light-alloy airframes began a growing demand for rolled slabs, bars and sheets and many varieties of extrusions, which had not been produced previously. Planning and public funding was required for new plants and methods of production of these materials, drawing at first on prior practice from the manufacture of other metal products. The production of engine components and propeller blades in light alloys became the business of some of the first shadow factories, followed later by additional plants for light alloy tubing and heavy forgings for undercarriages. Pressing machines would need to grow in scale to over 10,000 ton capacity for forging and 5,000 ton for extrusion.

4.1.3 Machine tools and adjuncts

Aircraft and engine manufacture in quantity would come to depend on large numbers of a wide variety of machine tools, including capstan lathes and other 'automatics' that could carry out a sequence of operations on a given work-piece without intervention by the operator. Britain had several companies specialising in the development and manufacture of these machines between the wars and was a nett exporter of them, although others were imported, especially from the United States. During rearmament the demand for these machines could at first be met from indigenous production, but as it progressed the requirements from all the Services rose rapidly and a large investment of public funds was made to expand this provision. Matching those needs to supply was a continuing problem up to and throughout the war [(27)].

It was also vital to maintain and develop a substantial ancillary to the machine tool industry, to provide the essential cutting tools and bits for machine tools of every kind. For accurate production over long runs, many of these were to be fitted with hard-wearing tungsten carbide tips. Most aircraft firms had facilities for regrinding worn tools for continuing service, but as the scale of operations grew, separate sources had to be set up to provide a centralised refurbishment service for groups of firms in a given locality.

4.1.4 Inspection

Quality assurance had always been a vital element in an industry where low weight was a critical factor in design. Aircraft and engines would be operating with small margins of safety, often for long periods of duty, and the necessary accuracy of manufacture to ensure that the designer's intentions were followed was reflected in the very close dimensional tolerances specified in the drawings used at every stage. There was also a basic principle for British aircraft that a given component must be interchangeable with any other for the same type, so that assembly could proceed with standardised items from stores, and a component damaged or broken in service replaced without any delay in searching for a matching part. Maintaining a culture where quality assurance was to be a routine feature required specialist equipment and skilled inspection staff. This vital element of British aircraft production has not generally been given appropriate recognition.

The first stage of inspection was by routine checks on dimensions made by operatives, trained in the use of basic instruments and gauges throughout manufacture. Especially where automatic machine-tools were in use, tool positions were fixed by trained 'setters'. Their role was to minimise unproductive down-time when tool wear caused dimensions of the product to approach specified limits. They would move around workshops to make adjustments to tooling and replace worn cutting tools. Inspection departments, equipped with more sensitive instruments, often optical in nature, maintained the next level of quality control. This sometimes meant having to check a critical dimension on every component produced, but as quantity production grew, by using a sampling system based on statistical procedures. Special jigs were made for checking distances in three dimensions between critical elements like holes bored in castings and the relations between their alignments. Together with welds in specified areas, castings were also some of the first components to be routinely inspected for possible flaws by X-ray.

Since 1913 a final stage of inspection had been introduced for all British service aircraft, operated by the Aeronautical Inspection Department (AID), which became part of the Air Ministry when that was formed [30]. Just as the flight test establishments at Martlesham Heath and Felixstowe were to check that prototype aircraft were safe to fly, the AID was to certify that approved materials were used when they went into production and that the parts were made in accordance with the designer's drawings and by recognised procedures. The standard values for the properties of materials to be used in design were verified at the AID test laboratories at Harefield in north-west London before being issued to suppliers and manufacturers. Provision had to be made at all military aircraft plants for space and facilities for AID inspectors located on the spot. A system of delegation was operated, in which the routine inspection during production was undertaken by the company's own inspectors with oversight by the AID [31]. All stages had to be covered, from the acceptance of incoming materials to final assembly, and products were formally signed off to leave the works, often confirmed by the AID stamp on an identification plate. This dual industry/AID role was critical in the maintenance of standards. At first the AID inspectors were often engineers with experience of design and manufacture, and they also needed to be aware of the need for good relations with the management, operatives and inspectors of the firm, so as not to hinder rates of output, while keeping a necessary distance as agents for the Air Ministry as customer. During WW2 the directorate recruited a large number of women to qualify as inspectors, via its training centre in Bristol [32].

4.1.5 Instruments and gauges for inspection

Inspection during manufacture and verification afterwards required the provision of a great variety of precision measuring instruments and gauges. From 1930 it was recognised that the supply of gauges would be critical in wartime, and that departments like the Air Ministry should be responsible for planning the requirements for production and inspection gauges in their area and arrangements for their supply. In the inter-war years, the industry had relied mainly on importing gauges and measuring instruments from suppliers in Switzerland, Sweden and the United States, but with encouragement from the Ministry and assistance from the NPL several British firms had established themselves significantly in that field. During the period of rearmament, further assistance was given, in accordance with the policy of building up capacity to match the expansion of manufacturing industry.

The requirements on the shop floor were mainly for basic instruments like micrometers and vernier gauges. The finest graduation for these was typically 1/1,000th inch (a 'thou'). These were supplemented by a great variety of 'go/no-go' gauges, with which compliance with the limits for dimensions shown on the drawings could be checked by feeling if the gauge would or would not pass over the section concerned. These were usually designed at the plant where they were to be used and made in its own toolroom.

Inspection departments used gauges of this kind too, but for the more critical dimensions the finest graduation could be 1/10,000th inch (a 'tenth'). There were machines for checking linear measurements, with anvils moved by high-precision lead-screws with a vernier read-out. Inspection departments would also have surface plates and tables, ground to a high degree of flatness over large areas. Height gauges placed on these could check a great variety of dimensions, generally by reference to slip gauges. These are small metal blocks made with great precision and supplied in graduated sets with which any given dimension could be reproduced by using them in combination. Complex shapes like those of gear teeth were checked with optical devices, generally known as 'shadowgraphs'. These could show a greatly-enlarged shadow of the component being examined, on a screen where it could be compared with a line drawing scaled-up to the same size and showing the limits within which the object could be accepted.

4.2 Planning at the end of the 1930s

From 1936, the Command structure of the RAF, which had been primarily developed for operations in overseas territories, was consolidated to include Home Defence. Initially, there were four Commands - Bomber, Coastal, Fighter and Training, followed in 1938 by Balloon (defence) and Maintenance Commands. Others were added later, as operational requirements demanded. Scheme F had included for the first time provision for permanent training centres for all levels of staffing, an enlargement of the existing Reserve force, and establishment of back-up resources in the RAF Volunteer Reserve (RAFVR) and University Air Squadrons.

Though the operations of the three Services remained under their respective commands at the Admiralty, War Office and Air Ministry, a Committee for the Coordination of Defence had been set up, as an aid to inter-service collaboration. One of the matters it considered was the complaint by the Navy about a long-term neglect of naval aviation at the Air Ministry, which in 1937 led to its regaining responsibility for this and the formation of the Fleet Air Arm. Coastal Command of the RAF retained control of the larger shore-based aircraft required for maritime operations over long ranges.

By the spring of 1938, deliveries of military aircraft were running at about 150 a month, though not all were as planned under Scheme F, as some earlier orders under the previous scheme were still outstanding. But the German annexation of Austria in March now caused a further review of the Air Ministry programme to be made, leading to successive proposals for increased procurement, culminating in the approval of Scheme L. Under this, the total provision would be 12,000 aircraft over two years [(5)]. Detailed consideration now led to specific provisions for fighters, medium and heavy bombers, reconnaissance aircraft and trainers, including about 700 naval aircraft. Offensive capability was still to the fore, the provisions for the RAF now intended to equip 57 squadrons of bombers and 40 of fighters. Relative to earlier Schemes, this raised the proportion of fighters, attributed to the influence of Sir Thomas Inskip, now Minister for the Coordination of Defence**,** appointed on the prompting of Winston Churchill. He had been influential in the return of naval aviation to Admiralty control, and now successfully argued that although strategic bombing would be an appropriate strategy for a lengthy war, in its earliest stages the fighters for home defence should have more priority [(6, 17)]. The role of the fighter had been hugely enhanced by the development in the mid-1930s of Radio Direction-Finding (RDF), later known as radar. The first of the stations for the Chain Home aerial network had been authorised at the end of 1935, and in the Spring of 1936 the team under Robert Watson-Watt had put in place the last technical requirement (obtaining the bearing of approaching aircraft) that made it possible to pin-point 'the position of an aircraft in the sky at a distance of 75 miles from the coast', according to Montgomery Hyde 'a breakthrough of unprecedented importance' [(9)].

Effectively, Scheme L marked the ending of funding as the limiting factor, the emphasis now being on meeting operational requirements. The Air Ministry made changes in its approach, accepting that time-scales would have to be shortened. Specifications would be simplified, mainly outlining the operational objectives for the type, and giving more scope to designers on how to meet them. The delay in waiting for a prototype to show its capabilities before being ordered into production would have to be cut. Ordering 'off the drawing board' had already been instituted for types needed urgently, and would become the norm. A lengthy setback due to the loss of a single prototype would be reduced by ordering more than one. Requiring manufacturers to have production procedures specifically in mind from the beginning of design would help to obtain early standardisation, with fewer modifications to interrupt manufacture. It is notable that these changes reflect quite closely the suggestions made in the article in *Aircraft Engineering* of 1934 cited above [(25)].

In 1938 Britain was essentially operating under peacetime conditions, but having regard to the alarming trend of international events, it seems surprising to the 21st Century awareness of security matters that so much information about the rearmament of the aircraft industry could continue to appear publicly in technical journals. In that year, *Aircraft Engineering* contained reports giving the locations and details of the shadow airframe factories managed by Austin and Rootes, the factory for de Havilland variable-pitch propellers, a new plant for Gloster Aircraft and others for Short Bros & Harland and Parnall. For aero-engine production, there were details of extensions to the Crewe factory of Rolls-Royce and the Standard carburettor factory near Coventry [(33)]. An account of quantity production methods for the Battle light bomber at the shadow factory managed by the Austin Motor Co included the layout of workshops and details of tooling, with illustrations of problems with particular parts of the structure and the jigs and fixtures employed in assembling them. That report added that a separate plant for production of engine components was opened on the same site [(34)].

With the rising political tensions, the immediate concern was to bring Scheme L to fulfilment, but the Air Ministry also made a reappraisal of the longer-term War Potential programme, which had previously been intended to provide an outline of the aircraft production considered to be needed in a prolonged war. For planning purposes, the Government had now set an assumed date for the beginning of a war with Germany [(5)]. Presciently, this was to start on 1 October 1939. With more detail than in earlier plans, Scheme L included numbers in seven categories of aircraft, with a total of 1,178 aircraft to be produced in December 1939 and output growing rapidly to reach the target of

2,000 a month a year later. However, this time-scale would have been beyond reach without the fundamental changes throughout the industry accelerated by the threat of imminent war.

5. Increasing interaction between Government and Industry

The close involvement of the relevant Ministry and the manufacturing industry was to become a vital feature of the success of aircraft production in wartime Britain. Some of the leading factors in this are outlined below, and for clarity the coverage extends in some areas beyond the immediate pre-war years into the early years of the war itself.

5.1 Industry problems

There had been consultation with industrial leaders, and with the assurance of firm orders, the 12,000 total under Scheme L was the greatest number of aircraft that the industry thought could be produced, with the application of maximum effort over the coming 2-year period. But the aircraft firms had never worked at this scale previously and it soon emerged that they had not anticipated the major changes of practice that it would require in every area of their operations. From development of their own premises and the availability of the shadow factories, they now had access to the floor area capacity to meet the target that had been agreed, and the required supply of leading equipment such as machine tools was at first within the scope of that element of British industry at the time. New factors for which they were not prepared were the level and detail of the organisation and planning needed for operating at this scale.

Design and drawing office personnel had previously been quite small in number, but now considerable enlargement would be needed. Production could not begin until the design had been 'standardised', and further design work would be needed for jigs and fixtures and detailed instructions prepared for component manufacture and assembly. Unit construction had to become the norm, in which an airframe was designed to be built from a group of major sub-assemblies, each of which was in turn designed for construction from a group of smaller ones (24). Once production had started, output would be greatest if all parts could be made in substantial batches. Changes to components, even some small ones, would have to be considered to be modifications to the design, and it was preferred that implementing them should wait until they were sufficient in number to justify a change to the mark of airframe being produced. But when that came, it would entail at best a slowing and probably an interruption to the production schedule (6).

New requirements emerged also for line supervisors, progress chasers, inspectors and a greatly enlarged labour force needing new skills, throwing up unexpected difficulties in recruiting and training personnel for these duties sufficiently quickly. Delays in things like delivery from suppliers of materials, which had been just accepted in the more leisurely times of the past, were now becoming major obstacles. Although there had been better investment in aircraft firms in the earlier part of the 1930s, it became necessary to obtain permission for additional borrowing to finance change at the rate now required (6).

There is an impression that orders of aircraft for the Navy and RAF Coastal Command were still relatively neglected. But although deliveries made up to and during WW2 were certainly very variable, firms like Blackburn, Fairey, Supermarine and Saunders-Roe produced naval aircraft continuously, and others occasionally, leading up to and throughout the war, and figured prominently in the shadow factory inventory. Biplane types continued to be provided for seaborne operations, where they had an advantage of a shorter span for a given wing area, easing problems in storage and handling. Aircraft of other companies, originally designed for other duties, such as the Hurricane, Spitfire and Mosquito, were also adapted for this seaborne use [(27)].

A specialised branch of industry for production of aero-engines had existed since the early days of powered flight and the basic technology was well-established. In the expansion programme the Bristol Engine Co was contracted to manage the first shadow engine group (No1), bringing in established firms from the motor industry. Prior familiarity with many of the basic processes involved helped to get this group up to speed with the greater precision required for aeronautical applications. This was to produce components of the Mercury and Pegasus engines for final assembly and testing by the parent company and one of the others. These were developments of earlier marks, continuing with conventional overhead valve gear. Bristol had also been engaged in a long struggle to perfect the metallurgy and manufacturing processes for the sleeve-valve layout, which offered greater efficiency and a more compact design. From 1939 its Hercules two-row sleeve-valve engine had been sufficiently developed and standardised for production by this group to be put in hand. Initially used in the Bristol Beaufighter twin-engine heavy fighter aircraft, successive marks of the Hercules, of progressively increasing power rating, were widely-used in the later part of the war, and the plants of this shadow group were enlarged accordingly.

At the beginning of rearmament Ernest Hives, on his appointment as general works manager at Rolls-Royce, saw the opportunity to undertake a complete reorganisation of the company's structure and plant. The firm had doubts about the shadow factory concept, but was able to form the No 2 engine group, while keeping the expanded operation under its own management. A greatly enlarged output of its Merlin engines in the longer term was obtained as its plant at the Derby headquarters was enlarged and new factories were opened at Crewe and near Glasgow. Eventually, firms other than Rolls-Royce provided Merlin production, at the plant of Ford at Manchester, and on a large scale at Packard in the US.

Both the Hercules and Merlin proved to be capable of progressive increases in power, and they became the preferred engines for a wide range of aircraft from fighters to heavy bombers. In their different ways, each of the groups was eventually managed as a coordinated unit, with engine research and development taking place at the parent company's original plant and progressively greater involvement of the associated plants in the planning and organisation of production [(6)]. From this beginning, the scope of the shadow factory component of expansion would continue to widen up to and beyond the beginning of the war. A significant feature was the involvement of more companies that had not previously had any connection with aviation, of all sizes up to large firms like English Electric, with its plant at Preston. As this developed, the nomenclature changed, and after the initial tranche the term 'agency factory' was used more often than 'shadow factory'. The table of over 90 of these plants compiled by Rogers seems to be the most complete [(29)].

5.2 Air Ministry developments

Its deepening involvement in aircraft production required radical changes to be made within the Air Ministry itself. Its operation had been organised around a number of Directorates with defined responsibilities, each headed by an Air Member, a senior officer to lead and represent it on the Air Council. Only from 1936 was there one with a direct concern for the actual process of providing the aircraft that had been ordered. This had begun to reduce late delivery by identifying the causes and advising the firms affected on ways of preventing it. Through this, the Ministry became aware of the significance of the network of subsidiary firms that were providing materials for fabrication and components for incorporation throughout the manufacture of aircraft, their engines, equipment and armament [(32)]. The Director, Lt-Col Disney, acknowledged that aspects of its planning had previously amounted to little more than 'pure guesswork' [(6)]. It would no longer be practicable to formulate a plan for aircraft procurement and pass all the responsibility for fulfilling it to the manufacturers. With the advent of Scheme L priority was given to having direct and continuous interaction between personnel in the Air Ministry and others in the industry.

In 1938 the role of Air Marshal Sir Wilfrid Freeman, already Air Member for Research and Development, was enlarged to include Production. He accepted that the knowledge and expertise required for the wider functions of this Directorate could not be found among officers of the RAF and other staff of the Ministry. In the past, only the Director of Scientific Research had been a civilian, but now Ernest Lemon, then a Vice-President of the LMS Railway and a former Chief Mechanical Engineer of the Company, was recruited to Development and Production as Director-General for Statistics and Production (DGP). Lemon was given a seat on the Air Council, and also became a member of its Committee on Supply, which met twice-weekly to review progress. Over time, this committee was to discuss issues in expanding production directly with leading representatives of firms and was ready to call to account both its own staff and those in industry.

Lemon's enquiries penetrated into many aspects of aircraft production and its supply chains. His reports were candid and direct. He had needed to make only a cursory examination of the situation to conclude that without urgent and major reforms there was no prospect for deliveries under Scheme L to be completed by the planned date of 1940. This is shown by Figure 9 from his biography [(35)]. The total output of the industry had remained at an average of about 170 aircraft a month for the past year, and showed no change after the beginning of the Scheme, though under the plan it should have started rising immediately and reach a peak of around 700 aircraft a month, by then due in less than a year.

The official history records that Lemon led 'a production department that was greatly expanded and completely reorganised' [(32)]. However, Connolly reported that the team specifically concerned with statistics and planning consisted at first of just five or six people [(12)]. One of these was Lewis Ord, a Canadian engineering consultant previously known to Lemon. Evidently this small group had the vision and initiative for the job. By 'short-cut methods . . . amounting to genius', Connolly said, 'a reasonable framework of planning factors emerged and enabled a programme of some validity to be produced before the war started'.

These 'planning factors' were still basic quantities such as floor areas, tooling and equipment levels, man-hours and raw material requirements, compiled and analysed, it seems for the first time, by Ord. However, they were a sufficient basis for the reforms that Lemon would propose to deal with the situation, as he went about implementing them vigorously [(35)]. The orders under Scheme L covered a remarkable 31 types of aircraft, but these were not amended. The focus would be on increasing the rate of production, but the efforts being made by industry to modernise its design and manufacturing methods were being hampered particularly by the difficulties over recruiting and training the greatly enlarged labour force required. Briefly, the two main elements Lemon advanced were a great enlargement of sub-contracting to alleviate that and data collection and analysis as the basis for the development of planning systems at all levels.

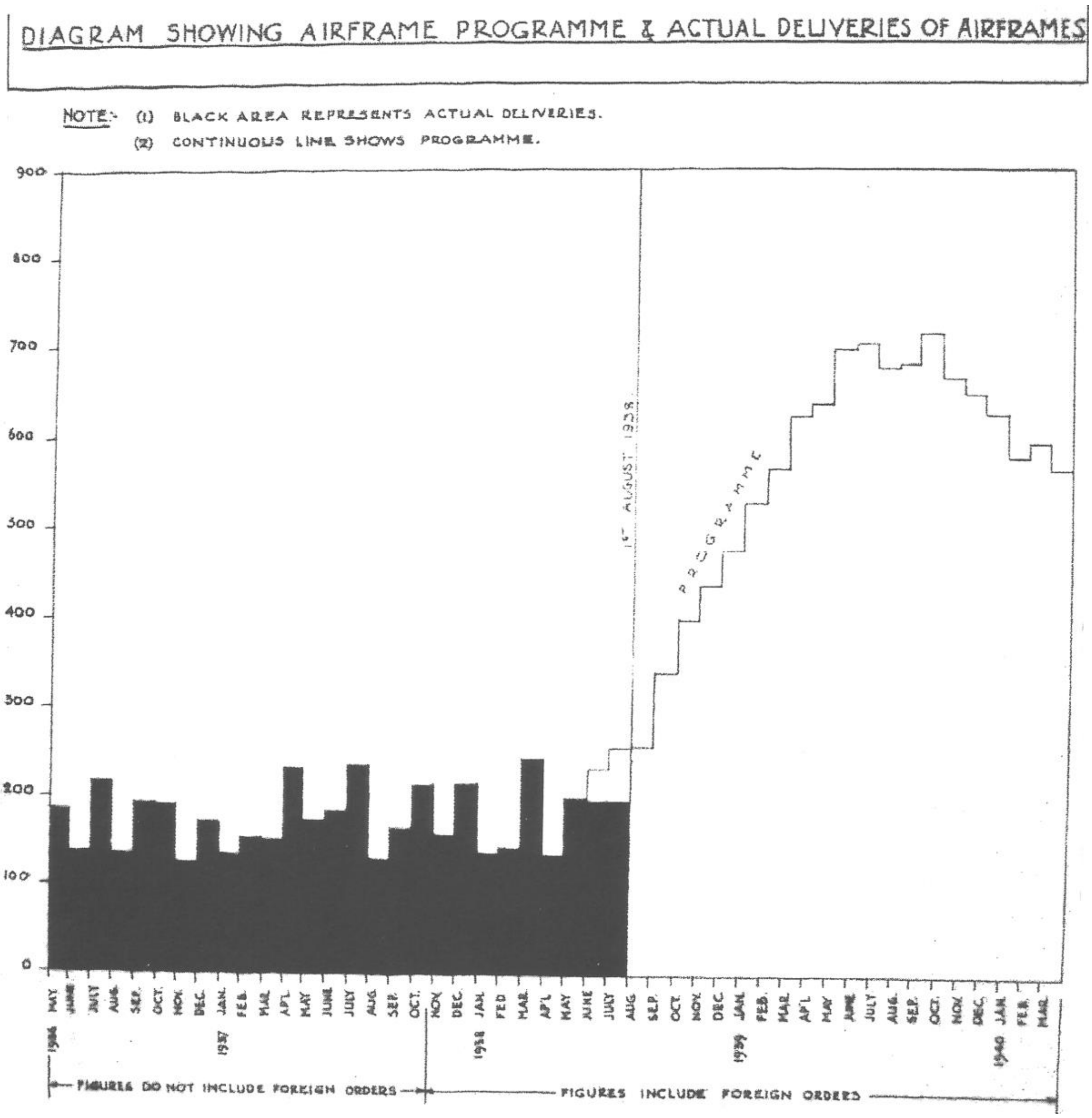

Figure 9 The challenge of Air Ministry Scheme L

Lemon, E, via Jenkins, T (reference 35)

The success of sub-contracting in a similar situation in WW1 was still remembered, and had already been urged again by Lord Weir and others. Lemon now recommended a wider adoption and a large expansion of this. He saw it as embodying a principle of 'bringing the orders to the labour', and considered that around 35% of the total man-hours required in aircraft manufacture could be put out to sub-contractors. In the Great War it had been found that numerous small companies with no previous involvement with aircraft engineering had proved to have a skilled and resourceful workforce that could readily adapt to the needs. The manufacturers had considered latterly that the much greater complexity of the all-metal aircraft of the time would now rule this out. But small and enterprising firms, alerted to the possibility, started to volunteer to become sub-contractors, and an expansion of the system was soon under way.

Inevitably, there were difficulties in implementing it quickly. The need for clear communication and coordination, with numerous places of work separated from the parent company by distance and previous practice, took much time and effort to resolve. Firms in general engineering, used to processes like welding and forming sheet steel, would have to understand and adapt to the different requirements of fabrication in light alloys. But over time it was again found that great contributions could be made by involving companies of all sizes, and even tiered sub-sub-assembly could be permitted. The aircraft manufacturers were encouraged to consider putting out a wider range of products, that increased with experience, from small parts required in large numbers and sub-assemblies at every level up to major components such as undercarriages and major parts of the structure. This widening of the plant and equipment being applied to aircraft production also substantially increased the workforce involved, often requiring less of the training that was a major obstacle to expansion when most of the new entrants had been previously unskilled.

'Group working' was another step inherited from WW1, requiring close collaboration between the plants of different manufacturers, which hitherto had been competitors. Among the Groups that would emerge, some were based on specific locations, as for the London area and the north-west of England, others for particular components such as engines and gun-turrets. Still in peacetime, the Air Ministry had no legal authority to insist on these reforms, but as it was already virtually the only customer, it was found that it was able to direct that large components such as the wings of a given aircraft should be made by a company other than the one that had designed and was assembling it. Lemon's staff made a rough categorisation across the industry, rating firms as A, B and C according to the current likelihood of meeting targets assigned to them, and set out proposals for giving them directions, that would include moving orders from one company to another if required.

For the system to operate successfully, it would also be necessary for manufacturers to begin monitoring work in detail at all stages of manufacture, and to record the information much more systematically than they had done previously. Summaries in standard formats had to be sent at specified intervals to the Air Ministry for collation and analysis. From these, procedures were instituted for exposing supply bottlenecks quickly, with the aim of enabling the Air Ministry to take timely corrective measures on a nation-wide basis. Orders were placed also for the advance purchase of raw materials to build up reserve stocks of critical items. For direct intervention of this kind, the Ministry's Supply Committee was to become 'an important new organ of administration' **(32)**.

Through these and other activities, the Air Ministry had greatly widened its former function to include direct involvement with production of the aircraft that it had ordered. Arrangements were made to place a representative, usually a middle-ranking RAF officer, in each company, to provide a direct channel for communication with the Ministry for resolving problems. These were originally to be called 'Air Overseers' but this was replaced by Resident Technical Officer (RTO), a less sensitive term. One of their functions was to approve (or gain approval for) modifications ('mods'). These were changes to design and manufacture of parts for aircraft in production, due to experience in service, advances in technology, changes in operational roles and many other causes. RTOs were to be concerned with mods at all stages, including the necessary changes to production planning schedules and workshop procedures, and signing off the relevant entries for design details in the master drawings register. They could also make decisions on the spot, for 'concessions' on minor departures in manufacture found on inspection from things like the less-critical dimensional limits on drawings, which otherwise would have to wait for a decision from the AID - (see Section 4.1.4). The Ministry, and later the MAP, were also represented at a more senior level at larger factories and Groups by 'DAP officers', representing the Director of Aircraft Production. A major action of those was participation in the Regional Organizations, coordination centres with local knowledge that greatly helped the Ministry's Sub-contract Branch in locating capacity for manufacture of components and sub-assemblies.

It was also necessary to begin the setting-up of procedures for assembling and recording the ever-increasing quantities of information that would be required at the Air Ministry to manage such a wide-ranging operation, and for processing and analysing the data. To be useful there, this information would have to be collated and made readily accessible for interpretation, for which purposes the use of Hollerith cards was adopted. These were punched cards, on which data could be input as patterns of holes via typewriter-style keyboards. The cards were filed systematically to provide a permanent record, from which the data could be recovered and sorted by electromechanical reader/printer machines. This system, which was to become one of the foundations for future automatic data processing, was marketed by The International Business Machines Corporation (IBM). It had limited adoption previously in Britain, mainly in the finance sector, and in public service for use in the National Census. The Air Ministry gathered up a large number of the machines and they were used extensively. The status of data acquisition and processing was emphasised in the abbreviated reference to Lemon's Division as D.Stats.P.

By the end of 1938 the rate of aircraft production was rising strongly, and Lemon could even claim later that the output originally planned for Scheme L would have been reached on time. The manufacturers began to look for further orders to occupy their expanding facilities, and an addition to the scheme was agreed in 1939 to provide for a further 5,500 aircraft from April 1940. The orders for these were to be mainly for types already in or near production, such as the Hurricane fighter and the Blenheim medium bomber, but also to assist with the introduction of the heavy bomber aircraft by which Britain could mount a strategic offensive from the air.

This further expansion formed Scheme M, the last to be defined by an alphabetical reference. In an associated review of the War Potential plan, D.Stats.P concluded that with the plant due to come on stream and steady progression in the recruitment of workers, the British industry could continue to increase its output, to reach a peak of around 2,000 aircraft a month if it worked up to the full capacity of its facilities. This figure had been for a decade the projection of the War Potential output required to sustain the air forces in a lengthy war [(5)]. Planning for progress towards that requirement had been taken much further for aircraft than for any other munitions programme [(27)].

Thus, the British aircraft industry had been reorganised at every level over a short period of time. There would be further expansion and other difficulties, but what had been a disparate set of competing businesses was on course to becoming a huge integrated national enterprise in which work on any type of aircraft could be assigned to any plant as opportunity arose. The processes for planning and managing such an operation, both in industry and the Air Ministry, would continue to be correspondingly challenging.

6. The American Connection

6.1 The British Air Mission

Though the British industry was judged to have the potential to reach a level of output that would be required in a state of war, it was recognised that it would take several years to reach that position. Accordingly, the Cabinet sent a British Air Mission to Canada and the US in February 1938 to visit potential contractors there [(36)].

It was found that there was currently little scope for this in Canada. Although companies had built three British types under licence for the Royal Canadian Air Force (RCAF), the aircraft sector was still very small. But the Canadian Government and some substantial engineering firms were supportive of establishing new plants for the purpose and for providing facilities for the training of aircrew, and these were followed up in due course. In the US, the Mission was impressed by the plants for civil aircraft production and the quality of the machines. Their output was rising in a climate of encouragement of the civil market by the Administration. The scope for manufacture of military aircraft was much more limited and their designs were less advanced than those already in production in Europe. Since WW1 a strong public aversion to the procurement of equipment for military purposes had been reflected in the official US policy of avoiding involvement in foreign disputes and the corresponding limitations of the Neutrality Act. The Mission's visits to aircraft and engine plants were nevertheless well received.

The outcome was a decision to place initial orders for two types. A North American Aviation private venture aircraft, when modified to RAF requirements, would become the Harvard intermediate trainer, and a version of the Lockheed Super Electra had the capacity to become a light bomber, but was represented as being for initial service for navigational training and reconnaissance. This was to be named the Hudson. For the RAF, it was to be fitted with a dorsal gun turret, but while in the US the aperture in the top of the fuselage for that was blanked off with a removable panel for delivery in peacetime. Orders were placed in June for 200 of each type with spares [(36)]. From the Mission's visit and discussion, it was realised that the potential for aircraft production in the US could be very great. A French commission also placed orders (for existing types of American aircraft) and the required output would considerably exceed the scale that purchases for the American forces had ever reached in recent times. It was expected then that the US factories would experience similar difficulties in raising their output to those faced in Britain, so there was concern that deliveries would not come in time to reinforce the initial rise in the planned UK programme. Accordingly, the British contracts had included a significant element for capital expenditure, to cover extension of some plants and construction of new ones, particularly for engine production. The US Administration acknowledged later that the stimulus to its aircraft industry given by these orders and others that followed the opening of WW2 had been a vital foundation for its own rearmament that was to be needed in due course [(37)].

An inspector from the AID was placed with each of the American airframe contractors, with a civilian from RAE as RTO and a test pilot for development and acceptance flying covering both companies. Acting on their own authority, they endeavoured to harmonise American practice with the rigorous procedures to which they were accustomed at home. Those included the traceability of all materials and purchased products from their primary sources and compliance with approved specifications. The signing-off of drawings was a standard practice, to ensure the coverage of things like the matching of dimensions and tolerances at all mating surfaces and the corresponding compatibility of gauges and jigs. The interchangeability of component parts and spares between all aircraft of a given type had to be assured. The American firms were quite ready to agree amended procedures for complying with the British expectations, once it was realised that the AID's role was basically one of overseeing a rigorous self-regulating system of inspection by company employees, on a basis of mutual respect [(36)]. In early 1939, similar arrangements were made with two aero-engine firms, Wright Aeronautical Corporation and Pratt & Whitney.

The first deliveries of Harvards to the UK arrived in December 1938 and Hudsons in February 1939, becoming the only American types to be received by the RAF before the start of WW2.

6.2 T P Wright

The American engineer Theodore Wright was held in high regard by Connolly, as the originator of expressions for the change of the unit cost of aircraft and components with the quantity produced [12]. Wright had written about these in a paper for the *Journal of the Aeronautical Sciences* in 1936, when he was Vice-President for Engineering at the Curtiss-Wright Corporation [38]. Relationships of this kind, often known loosely as 'learning curves', were to be one of the foundations of advances in the planning and management of production engineering.

Wright presented data that he had gathered on the principal elements of cost in the production of aircraft in the US, given initially as labour, raw material, purchased material and overheads. For each of these contributing elements the cost F, given as a fraction of its cost for the first aircraft made, was related to the number N of aircraft produced. This was represented by a mathematical expression of the form $F = N^{x}$. This 'power law' relationship is more conveniently shown on a graph with logarithmic axes, as it then becomes a straight line, the slope of which is $x = (\log F)/(\log N)$. In the usual situation where F is falling as N increases, the slope has a negative value. The costs contributed by each of the elements of raw materials, purchased (i.e. processed) materials and labour (manpower) follow straight lines in the example given by Wright, reproduced as Figure 10 [38]. Originally the concept had been applied to the cumulative average cost, but in practice it was found to apply just as well to the current cost.

Wright's presentation was a generalisation of a previous practice. That gave the change of the unit cost expected after a doubling of the number of items produced, most often expressed as a percentage. If the output follows a power-law curve, this change is the same for doubling from any N to 2N. For example, if $x = -0.3$, the cost at 2N is 81% of its value at N (i.e. $2^{-0.3}$). Both values, of the slope x and the percentage cost after doubling, are given for the components in Figure 10. The percentage cost measure continued in use, as it was more easily visualised in the work-place.

It is to be noted, however, that the overall cost of the product, which is the sum of the contributions of the elements, will not be represented by a straight line except in a case where the slopes x happen to be the same for each of the elements. This is because the sum of logarithms does not give the logarithm of the sum. In Wright's example, the lower changes of the cost of materials (95% and 88% for doubling) as the production proceeded relative to that of labour (80%) caused the slope of the total cost curve to rise from an initial value for doubling the production of 83% to 90% at the end of the production run.

With experience, the above approach was found to apply quite well to other factors, such as the number of man-hours required. Another expression given by Wright related the labour requirement H for the construction of an aircraft (typically in man-hours) to its structure weight W (lbs), showing in his example H to be proportional to $W^{2/3}$.

Although reduced to mathematical form, rules like these were empirical relations without scientific foundation. As they were derived from overall average figures, there could also be significant variations for particular cases, but they would provide a working basis for advances in the planning of aircraft production on the large scale when required in WW2.

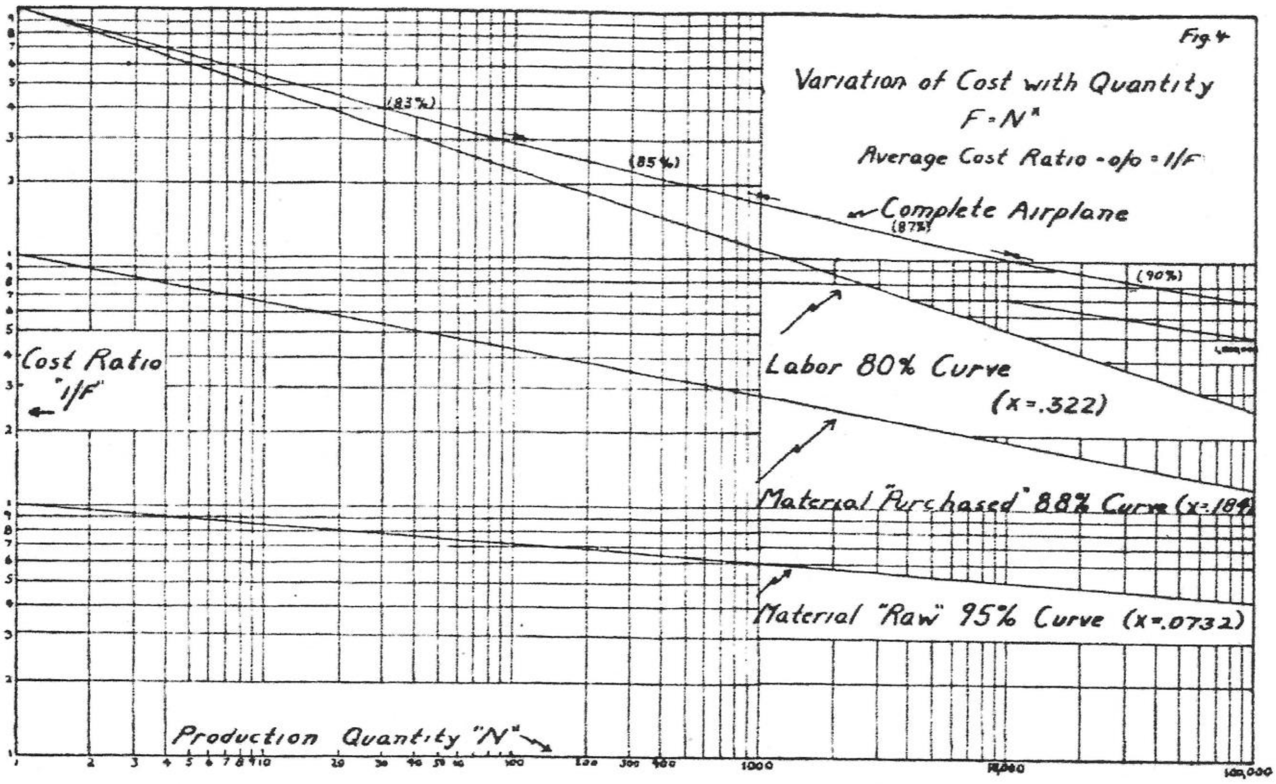

Figure 10 Change of unit cost of aircraft with number produced
Wright, T P (reference 38)

Reviewing the contribution of developments in production technology since WW1, Wright pointed out that cost and the time required to produce a part were closely connected. He gave illustrations of how labour-intensive processes, such as fabrication involving the preparation of subcomponents and welding or riveting them together to construct a part, could now be replaced by forming and pressing in one piece, with a saving of time. It had been shown that this outweighed the cost of making the dies required for those processes.

Wright concluded his paper with a comparison of the costs of a light aircraft and an automobile, each with 4-5 seats. The former came out in the range of four to six times that of the latter, but he pointed out that this was not the whole story, as the aircraft had an advantage of efficiency from a much shorter journey time when in use. He noted that time was becoming 'of ever increasing importance'. However, he emphasised that the lower cost of producing the car had benefited from 'the vast backlog of experience in the art not yet acquired or directly applicable to planes in large quantities'. The Air Ministry had already shown its awareness of this from experience in WW1 and in its involvement of the British motor industry in the planning and management of the shadow factories. The appointment to senior positions in the Ministry of civilian personnel such as Lemon from the rail transport industry was another move to import direct industrial experience into the formation of its planning procedures.

In November 1938 Wright delivered an invited paper on American methods of aircraft production to one of the Royal Aeronautical Society's meetings, based on information he had gathered across the US industry, principally on the manufacture for the civil market (39). Accompanied by 127 Figures, his long account showed extensive workshop facilities, specially-developed tooling, equipment such as overhead monorails bringing parts to stations on production lines, and the consequent rows of aircraft at final assembly. Larger firms had their own wind tunnels and space for lofting floors and full-scale mock-ups. This presentation must have provided much food for thought for many in the audience.

Wright went on to describe in detail methods of fabrication currently in use, and also covered the broad question of how an American aircraft plant was typically organised. A notable difference with arrangements in Britain was the placing of great value on having a distinct planning department that sat between those for the design and for the manufacture of a new type. Its basic function was to translate the information from the engineering drawings into detailed instruction sheets for the workshops, a process which was considered to require a specific set of skills. This included the design of tools, dies, jigs and fixtures, with their associated patterns and templates, the specification of the tools and machines to be used for each operation of manufacture, and equipment and instrumentation needed for gauging and subsequent inspection. The issue of an instruction sheet also generated the orders for purchasing and requisitioning materials and other stock items required for producing the component. Use of punched cards saved much time in compiling the necessary lists for the orders. Work study and detailed knowledge of machine and bench capacity was required, so that the proper rate of issuing orders to the workshops could be gauged. The basic principle, Wright said, was to 'create a condition, as economically as possible, by virtue of which work is pushed through the shop by each prior department rather than pulled through from final assembly'.

Questions from the floor and replies revealed difficulties common to the US and UK, but some showed up the differences, including preferences for methods of fabrication. One queried the need to provide the 3,500-ton presses that had been shown, when in Britain machines of a tenth of that rating seemed to have been sufficient. On a Table shown by Wright, giving the distribution of specialisations among the staff of a design department of 200 men, a questioner asked how many projects this team would be handling, to which the reply was that the number was for a single project.

Hosted by the President of the Society A H R (Roy) Fedden of Bristol Engines, a dinner was given for Wright after his presentation. The guest list reads like an alphabet of luminaries of the British aircraft industry at the time, including Robert Blackburn, Hugh Burroughes, Sydney Camm, Charles Fairey, Frederick Handley Page, Geoffrey de Havilland, Ernest Hives, Oswald Short, Reginald Verdon Smith, with many others. Sir Charles Craven from the Air Ministry must have pondered the extent to which the ideas on the organisation of production might be utilised just as well in the rearmament programme as in construction for the civil market, which had been the substance of Wright's presentation.

Elected President of the Institute of the Aeronautical Sciences in 1938, Wright was a frequent visitor to Britain and was later elected Honorary Fellow of the Royal Aeronautical Society. He would be invited to present its first post-war Wilbur Wright Memorial Lecture (the 33rd) in 1945, choosing the subject *Aviation's Place in Civilisation* [(40)].

6.3 In wartime

After the opening of WW2, the British and French air commissions had discussions about larger and longer-term arrangements for supply of aircraft from the US, in which President Roosevelt took a direct interest. Early in 1940, officials in the Administration produced a plan for building up these deliveries, in conjunction with an expansion of the industry for re-equipment of the US Army Air

Corps (later Force USAAF) and US Navy (USN). Much had been made of this in the American press, reporting that by the end of 1940 supplies to Britain were to reach 3,000 to 4,000 aircraft a month, adding that US aircraft and engines were the best in the world. These claims were dismissed with some irritation when mentioned at a Board meeting of the SBAC [41]. Commercial aviation was being actively promoted by the Administration, but the military arm of the American industry was smaller and weaker, as found by the French and British purchasing commissions earlier. With reference to military machines, Connolly's opinion was that in planning production 'the Americans in those days were even less advanced, and their programmes even less realistic than our own' [12].

D.Stats.P prepared a brief for the Prime Minister, having regard to difficulties that might be faced in the US, similar to those that had been experienced in Britain [42]. It concluded that the reported plan was seriously unrealistic, as it would require the number of trained employees and the supply of light alloys to be tripled by the end of the year. Estimates considered feasible by D.Stats.P indicated that perhaps 1,000 aircraft per month could be delivered by the planned date of October 1943, but that a safer figure would be 800 to 900 per month. Connolly later compared this estimate with the actual delivery figures for US-supplied aircraft up to the end of 1942 [12]. As given in Figure 11, this indicated that the MAP projections had been well-founded. It should be noted, however, that there had never been an expectation on the British side of a heavy reliance on aircraft supplies from America in the period of build-up to the full War Potential requirement from production at home [5]. The main hopes at this stage from across the Atlantic were for food, fuel, raw materials and machine tools, which were generously fulfilled.

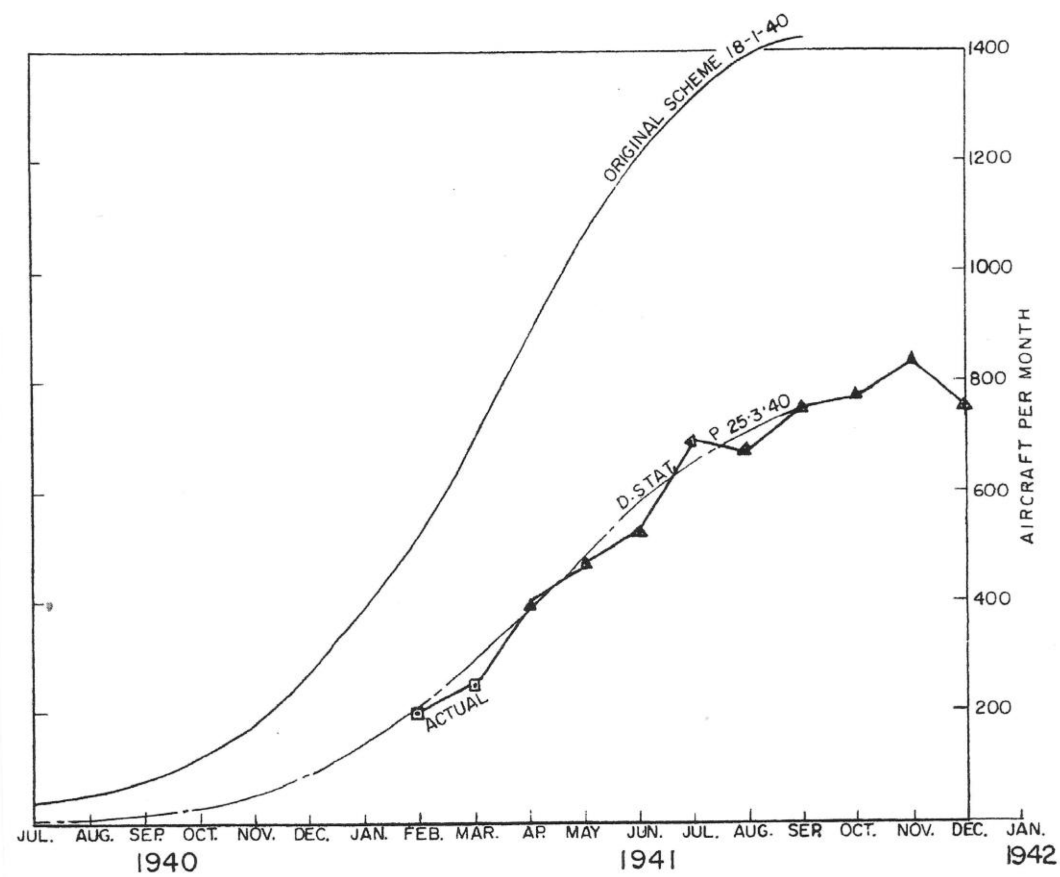

Figure 11. Intentions and actual delivery of US aircraft, 1940 – 41
Top: Planned by US Administration
Bottom: Estimate by Air Ministry D. Stats. P. and actual deliveries
Connolly, J V (reference 42)

In September 1940 the activities initiated by the British Air Commission were taken over by an enlarged British Purchasing Commission, now constituted to cover increasing production of munitions for all services from facilities in Canada and the United States in the longer term [(36)].

In Canada, the first orders for the RAF were for Hampden medium bombers and Hurricanes, to be built under licence by the Canadian Associated Aircraft Ltd and the Canadian Car & Foundry Co Ltd. Together with other firms and the local version of shadow plants, they went on to produce more than 16,000 aircraft for the RAF and the RCAF, including those required for the extensive training facilities that were established there. Nearly 200,000 aircrew and ground staff were trained at about 200 sites in Canada under the British & Commonwealth Air Training Plan. The northern route of the Atlantic Air Bridge, also operated from bases in Canada, was opened in November 1940. Later there was a southern branch via Nassau, which became the means by which hundreds of US aircraft were flown to Britain. Similar aircraft and training facilities were also provided by Australia and other countries of the Commonwealth, though on a smaller scale.

After the fall of France, further orders were agreed, including the taking-over of those originally intended for the French. Although those aircraft were being built to their conventions (for example, with cockpit instruments scaled in metric units and the throttle lever pulled rearwards to increase power), it was considered best not to make changes to the contracts and a special unit was set up at the Burtonwood repair depot to convert the aircraft to British standards. Later, this unit was heavily involved in fitting-out American-built aircraft with Government-owned 'embodiment-loan' items, particularly weapons and radio and radar equipment.

In 1940 North American Aviation designed a new single-seat fighter to British requirements, which became the NA73. On the first deliveries to the RAF the type was found to have poor performance at high altitudes, and when it went into service at the beginning of 1942 it could not be used in the interceptor role. The suggestion of fitting a Merlin engine, with the 2 speed 2-stage supercharger, transformed this and the type subsequently went into mass production with the Packard version of the engine at the new NAA plant at Inglewood, California. Somewhat larger than the Spitfire, and with a greater internal volume, it could carry much more fuel, and with low-drag characteristics it had good endurance, going on to become the famous Mustang long-range escort fighter. It was also widely adopted by the US fighter groups, with a total of some 16,000 being produced in all.

Capital elements were included in these contracts, being still necessary to assist the expansion of facilities in the US, so the sums committed rose to the point that British financial reserves became dangerously depleted. To ease this drain, Roosevelt subsequently devised an arrangement called 'Lend Lease', presented on the homespun principle that if your neighbour's house was on fire, you would lend him your hose, and have it back after the fire was put out [(36)]. After this scheme was authorised in March 1941, aircraft built in the US had first to become part of the inventory of the USAAF and retain their American designations until delivery to Britain.

The US was itself drawn into the war after the Pearl Harbor attack in December 1941, and the arrangement was revised in September 1942, to become one between allies in a common cause, providing 'reciprocal aid, so that the need of each Government for the currency of the other may be reduced to a minimum'. Reciprocation by Britain was mainly through the provision of airfields and other military installations for US forces at home and across the Commonwealth. Deliveries to Britain continued throughout the war, passing through a peak towards the end of 1943. According to K J Meekcoms, who lists every machine obtained from the US, the total provisions of all types for the RAF and RN were about 37,000, adding about one-third to the British total [(36)].

7. Into the 1940s

7.1 The first year of war

Actions had to be taken hastily under the extreme pressure of events, and inevitably mistakes were made, but it can be seen that firm plans had for some time been prepared progressively by Government departments for many sectors of the economy that would put the country and all of its people on a footing to engage in 'total war'. Where a specific date had been required for planning purposes, the beginning of October 1939 was adopted, and it had been taken seriously. But although financial limitations on military expenditure had been relaxed and for aircraft production abandoned, it became clear that Britain could not be made ready to sustain an immediate full-scale conflict in Europe by that date. Chamberlain's government adopted a policy of appeasement in dealings with Hitler, and that was much criticised, though there had been little option but to try it, if only to gain time.

When in March 1939 Hitler broke the agreement made at their Munich meeting in the previous September it was considered that war was now inevitable, and the Government began to implement its plans for wartime. The Emergency Powers (Defence) Act, 1939, passed with effect from 24 August, together with an extension in May 1940, gave the Government control over every aspect of the life of the kingdom and of its people, as its equivalent the Defence of the Realm Act had done in WW1.

Despite this nation-wide anticipation of war, articles giving details of British production methods continued to appear in technical journals. In April, one on the quantity production of the Spitfire I included much information on the manufacturing processes in use, copiously illustrated by diagrams and photographs. The subcontracting scheme is described, whereby major components such as wings and tail units were being made out and brought together for assembly at plants at Woolston, Itchen and Eastleigh [(43)]. The new journal *Aircraft Production* contained articles on production for nine aircraft types, including illustrations from current work on the Hurricane [(44)], supplemented by one by Sydney Camm on rationalising production, in which he advocated a great reduction in the variety of steels and light alloys that suppliers were currently expected to provide [(45)]. Similar revelations of British practices continued up to the third volume of that journal in 1941.

German forces invaded Poland on 1st September. Having guaranteed to come to the aid of Poland if she were attacked, Britain and France warned Hitler that there would be war if his forces were not withdrawn. That having been ignored, the war formally began on 3rd September. From his perspective as a historian of the following six years of war and their consequences, Postan called this 'one of the greatest dates in the history of the western world' [(5)].

Events within Britain immediately before and following the outbreak of WW2 have been widely reported and discussed, so only a framework for the consideration of production planning is given here. Despite early judgments to the contrary, actions necessary at the outbreak of war had been planned, and these were put into effect progressively. Included in those for the relocation of Government departments away from London, the large building of the Grand Hotel at Harrogate in the north-east of England was now requisitioned for the Air Ministry. Apart from a small residual staff, all were moved there immediately after the declaration of war. Despite this disturbance, the staff of D.Stats.P continued to work on the implementation of plans to reach the longer-term rate of aircraft production projected in the War Potential assessment, which now had to become reality. Initially, this took the form of the 'Harrogate' plan, the first of a series identified by names instead of lettered schemes. The target was a rise from 970 aircraft a month at the beginning of 1940 to 2,170 by March 1941. This and succeeding plans will be summarised in later sections.

As Hitler had been assured by his foreign ministry and intelligence services that Britain and France would not go to war, there had been no firm German planning for a war with Britain. But RAF Bomber Command was in action from the first day. Initially they were required to avoid civilian casualties, so the first targets were mainly shipping and naval facilities on the Baltic coast of Germany in the region of Wilhelmshaven [(46)]. In persistent bad weather, their attacks had to be made at low altitude, where they were soon to meet fierce opposition in the form of fire from the ground and naval vessels, and in the air from Messerschmitt Bf109 and Me110 fighters in squadron strength. Heavy losses experienced in this early combat were increased by problems of navigation in conditions of poor visibility.

On 9 April 1940, German forces quickly occupied Denmark and made combined naval and airborne assaults into central and southern Norway. British forces were landed in northern Norway from the 15th April, to join the fierce resistance being fought by Norwegian forces in the south. But having provoked massively-reinforced German forces, and without adequate air cover, they could not maintain a foothold and were forced to withdraw to the north again.

Bitterly criticised in Parliament about the handling of these actions, Chamberlain resigned. Sadly, he was taken ill shortly afterwards and died in November. On 10th May 1940, Churchill was invited to become Prime Minister of a revised all-party national Government, in which he also took the key post of Minister for War. On the same day, German forces invaded the Low Countries, mounting a highly-mobile advance, with paratroops and armour supported by dive-bombers with fighter cover ('Blizkrieg' - lightning war). These rapidly-advancing ground forces could be attacked accurately only from low altitude, but German ground forces were amply defended by anti-aircraft weapons of many kinds and by fighter aircraft in strength. Unprepared for this form of warfare, the RAF was outnumbered and outclassed.

Ten squadrons of Fairey Battle light bombers were the main component of the Advanced Air Striking Force (AASF) that had been sent to France on 2 September 1939. Though one had the distinction of having the first RAF combat victory of the war, shooting down a Bf109 on the 20th, the type was found to be gravely vulnerable when opposing the German advance into Belgium the following May. Losses of Battle and Blenheim aircraft in ground attack and of Hurricanes in providing cover mounted quickly. Soon threatened with containment by a second German invading force which emerged unexpectedly into France through the Ardennes forest, the British and French forces in the sector fell back westwards through Belgium, culminating in the evacuation from Dunkirk, ending in early June.

Though less well remembered, fighting continued thereafter in France, where the German advance towards the Atlantic coast was less spectacular. But the Luftwaffe had virtually destroyed the Armée de l'Air, and could give ground support in strength wherever required. RAF operations from airfields in France continued until 18 June, but could not be sustained in the face of heavy losses, and a second evacuation of Allied forces took place through ports in Normandy. France formally surrendered on the 25th June. In the short six weeks of what Churchill called the 'Battle of France', the RAF had lost almost 1,000 aircraft and about the same number of aircrew. The British campaign in Norway ended with its last withdrawal on the 8th June, and there was now no contact with the enemy on land. Britain could oppose Germany only through a blockade by sea and attrition by bombing from the air.

After the fall of France, the Luftwaffe could begin flying from bases within a short distance of the British coast, and as these became operational it commenced the bombing of airfields and aircraft factories at known locations across the south and south-east of Britain, while facilities for a seaborne invasion were being built up in Belgium. A preparatory full-scale operation to gain German air superiority began on 11th July. The story of the Battle of Britain, which frustrated this over the following months, has been reported in great detail elsewhere (e.g. reference 4).

As part of this assault, the bombing of aircraft factories caused serious damage and interruption of production [(27)]. To minimise this, the practice of 'dispersal' was intensified. Work at component level was moved out to locations over a wide area surrounding the facility to which they would be delivered for final assembly, using space at a great variety of requisitioned buildings, some quite small and even including homes. At first, this had been done as an emergency measure by local initiatives, but it was soon found that this enlargement of sub-contracting could be managed well and was productive, so that it became general policy. Dispersal to less-recognisable sites for storage of manufactured components, and even complete airframes and engines, was also seen to be a safeguard to the continuity of delivery despite continuing enemy action. An early example often noted was that of Supermarine near Southampton, of which the main plant had been heavily damaged in daylight raids in September 1940. Production of parts of the Spitfire had already been dispersed to requisitioned garages and a bus station in the locality, but now this was extended to sites across a wide area of central southern England, ultimately 64 in number, with a total floor area of nearly 1.4 million square feet [(47)]. Gloster Aircraft also used 48 dispersal units in its Hurricane programme [(27)]. Being clearly effective, the inclusion of small premises was accepted by the Ministry, and as the war progressed local dispersal was fully absorbed into the policy of central planning for relocation. After trials with factories built underground, it was seen that obtaining new manufacturing space by requisitioning existing buildings greatly reduced vulnerability to bombing and was much the least expensive option.

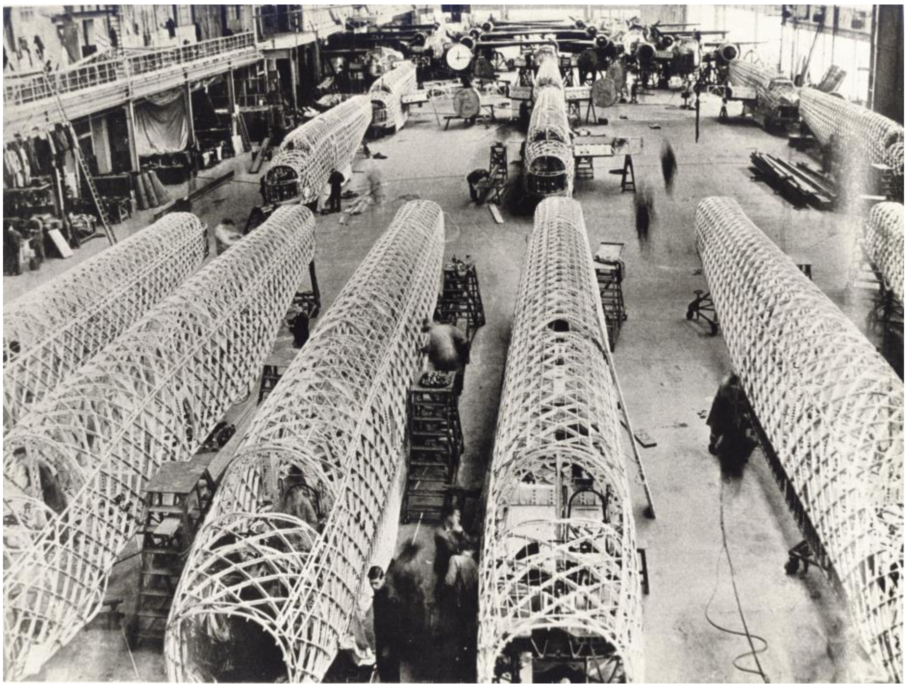

Figure 12. Production of Wellington medium bombers, showing the geodetic construction

As the potential for enemy action had been anticipated in the selection of locations for new production plants, it is remarkable that articles giving details of work being done in them continued to appear in the technical press. The use of geodetic structure in the Wellington bomber, shown in Figure 12, was the subject of one example published in 1940 [(48)]. This showed how the structure of the Wellington presented 'novel and sometimes difficult production problems' and gave the layout of the works and equipment used in the assembly of the fuselage and wings, fully illustrated by drawings and photographs. Permission from the Air Ministry to publish this article was acknowledged, so perhaps it was accepted that the German intelligence services would know all about it anyway.

The Boulton Paul Defiant, shown earlier in Figure 4, finally entered service in the summer of 1939. Though it accounted for a number of German bombers and fighters, its performance was compromised by its dorsal gun turret, and it was soon out-manoeuvred. When its own losses mounted it was transferred to night-fighter duties, where it had some success after the introduction of the Mk4 airborne interception radar (AI). As with the Fairey Battle, early-1930s conceptions without further development had become obsolete when the war began. However, their manufacture was continued, and even enhanced, partly to maintain momentum while waiting for new types to reach production status. As a result, over 2,000 Battles and 1,000 Defiants were built (49, 50). More than half of the Battles built were shipped to Australia and Canada in support of the Commonwealth Air Training Plan, and in Britain both types continued to provide useful service in a variety of other non-combative roles.

7.2 Ministry of Aircraft Production - the first steps

Churchill had been a continual critic of the pace and scope of British rearmament, and three days after taking office he formed the separate Ministry of Aircraft Production (MAP). The intention was to establish this with staff already concerned with the task transferred from the Air Ministry, leaving that to concentrate on managing the operational functions of the RAF in wartime and the planning of the resources required to carry them out. The position of Minister of the new Department went to a friend, the Canadian and newspaper magnate (William) Max Aitken, now 1st Baron Beaverbrook.

He soon showed his self-assured and impulsive nature, by moving immediately to prioritise the production of fighters. This included manoeuvring the take-over by Vickers-Armstrong (Aircraft) Ltd of the Castle Bromwich shadow factory, planned for large-scale production of Spitfires, which had not yet produced any while under the management of Lord Nuffield's Morris motor company. The first aircraft emerged from there in June 1940, perilously late for the imminent battle. Meanwhile, every available fighter that could be pressed into service had been rounded up by MAP and RAF personnel.

Nuffield had also been recruited to set up a civilian organisation to increase the rebuilding of crashed aircraft and the salvaging of reusable materials and equipment from those too badly wrecked for restoration. This was already being done by the RAF Maintenance Units (MUs), but adding a civilian component was another action modelled on its equivalent in WW1. So the start that had been made was urgently strengthened and expanded under Beaverbrook, to become the Civilian Repair Organisation (CRO), comprising a network of Civilian Repair Units (CRUs) across the country. These were located at now-vacant civil airfields, factory buildings, shops and numerous other spaces. This grew to be a large and complex organisation employing thousands of men and women, many working in garages and very small companies and often without any previous relevant experience. Guidance was provided initially by a few knowledgeable technicians, mostly having been employed in the servicing of commercial and private aircraft, working in conjunction with the RAF MUs. They formed teams that dismantled wrecks in the open at crash sites, and transported sections and components to depots where useful parts were recovered and repaired for incorporation into refurbished aircraft. Rigorous quality-control was maintained, with reference to copies of the original manufacturers' drawings. Aircraft totally wrecked or damaged beyond repair were 'reduced to produce' at designated sites to recover any materials that could be re-used. The governing principle was that nothing should be wasted.

An example of a larger CRU familiar to Lemon is shown by his biographer in a view of the workshops of the LMS railway company taken over for the purpose at Derby, with rows of jigs holding Hurricane wings under repair (35). Some depots on former airfields worked a 'fly-in' service, to which an aircraft could be taken if it had a defect or battle damage but could be flown with care, and if it could be repaired within 24 hours the pilot could wait and fly it back. This was likened by Wood and Dempster to the operation of an out-patients department of a hospital (4). CRUs later widened their scope to incorporating modifications to bring aircraft up to the manufacturers' latest Mark. Machines from the US, crated and transported to Britain by sea, were also re-assembled by the CRUs (51).

Practicality and resourcefulness enabled the CRO to return a large quantity of damaged aircraft of all types to service with remarkable speed. As early as during the Battle of Britain, a third of the aircraft issued to fighter squadrons were supplied by the CRO. Over the duration of WW2, it returned nearly 82,000 repaired aircraft and 167,000 engines to service.

There had been another adjunct to aircraft supply, following the ending of private flying from the beginning of the war. Some commercial flying was allowed for a short time, but all civil aircraft that might be of use to the RAF were then impressed and given insignia and service serial numbers, adding significantly to its capability in the training and communication sectors at a critical time (52).

8. Later MAP programmes

8.1 The 'Five Types' priority

Beaverbrook had begun work without establishing a formal structure for his Ministry. The senior personnel transferred from the Air Ministry were Sir Charles Craven and Sir Wilfrid Freeman, who continued the general format as it had been previously. But Beaverbrook brought in two business friends, Trevor Westbrook with experience at Vickers-Armstrong (Aircraft) and Patrick Hennessy from the Ford Motor Company. Working mainly with these, he operated at first from his home overlooking Green Park. The large buildings of ICI on Millbank had been requisitioned for MAP, but only a small liaison staff was brought back from Harrogate, and the main body remained there until the threat of invasion receded and they returned to London.

Describing the operation of Beaverbrook's new group, Clive Ponting records that 'Few records were kept, the functions of most individuals were left undefined and business was conducted mainly over the telephone' (53). Although the staff taken over from the Air Ministry were effectively 'a going concern' (32), this circumventing of the procedures of the former Air Ministry disrupted the established procedures for planning. Cairncross described it as 'too much drive and too little coordination' (54). But some of the earliest actions under Beaverbrook, as described previously, were an indication of his way of going immediately for the most urgent requirement. This would have been generally agreed at the time to be the necessity of providing the maximum possible fighter strength to meet the expected onslaught of the Luftwaffe following the fall of France. As well as the Hurricane and Spitfire, which would be the main agents for that, under Beaverbrook three other types were selected for priority - the Bristol Blenheim, Vickers-Armstrong Wellington and Armstrong Whitworth Whitley medium bombers. This would require redirection of materials supply, so there would inevitably be a drop in output from other programmes.

As noted in Section 3.2, the medium bomber types had first flown in 1936 and were in production before the war began. All three had flown to German targets from the first days of the conflict, though initially under direction from the Cabinet that they should not cause civilian casualties. When the policy had been changed after the indiscriminate bombing in the German invasion of the Netherlands, aircraft of more modern design would have been preferable, but having numbers in the air at this critical time was imperative. As noted earlier, production of the Battle and Defiant types were also continued. The processes involved in the manufacture of these established types being well understood, they provided the best opportunities for maximising the output of aircraft. Double-shift working was now to be considered the norm.

Of the priority types, the Whitley was kept in production well into the war years, after having been re-engined with Merlins for the Mk IV version of 1938. The Blenheim underwent a series of modifications that enabled it to continue in use in a variety of roles, and was succeeded by a developed version that became the Beaufort, supplemented by the Beaufighter, heavily-armed to be both a night-fighter and effective against ground forces, surface vessels and submarines (see Figure 7). The Wellington was the only British bomber type to be in continuous production throughout the war, nearly 11,500 being built in all. But the strategic aims of the RAF would not be fulfilled until sufficient numbers of the heavy bombers could be brought into service.

8.2 Smoothing materials supply

Beaverbrook required to be made aware of any interruptions to production affecting his 'Five Types' project. The main one was caused by delays in deliveries of special and alloy steel products in the form of strip and sheet pre-worked by rolling and extrusion. Hennessy and Craven had been sharing most of the areas of responsibility concerning production formerly held by Freeman [(32)]. Hennessy, now vaguely designated Industrial Adviser to the Minister, was sent to Harrogate forthwith to 'clear this up'. Connolly, who had been directed to RAE at the beginning of the war, appears to have been transferred to MAP at some point around this time, and subsequently provided an inside view of this and other contemporary events. He considered that these should be recorded 'both from the historical and the theoretical production-engineering point of view' [(12)].

It was found that the scale and complexity of operation was now such that the number of requests for allocations of worked materials had become too numerous to be regulated effectively, even by the staff of 20 production officers devoted to it. A special group set up to investigate this found that requests for supply of materials had been made on the basis of orders and schedules without regard to the actual situations in the workshops. Where there had been inevitable interruptions in production for other reasons, requests had continued to be made as usual and stocks had been retained locally, while there were urgent shortages elsewhere. The problem was brought under control by an arrangement that supply was to be made only where an immediate requirement could be demonstrated, a policy duly adopted throughout airframe production. When commenting favourably on this later, Connolly probably had in mind a similarity with the 'just-in-time' delivery system, with little or no stock held, that seemed revolutionary when adopted by Japanese industry decades afterwards.

The group tracked the process of special steel provision through every step back to the rolling and forging by producers. In doing so, a similar crisis in the supply of light alloys was also seen to be impending, and the whole procedure of worked material flow was rationalised over a period of 'a few months'. The improved data reporting requirements revealed that there had been a very wide range of stock dimensions for materials being ordered from suppliers, due to settled practices from the past which had differed between the aircraft manufacturers, a point made earlier by Sydney Camm [(45)]. Now minimum lengths were specified for orders of worked materials, so that producers could set up reasonable batch sizes, requiring fewer changes of rolls and dies. A major step was to reduce drastically the number, profiles and sizes of rolled and extruded sections that would be available. Directions were sent to design and production staff that only standard sections from the approved set could be specified, and many rolls and dies were removed from suppliers to ensure compliance.

Connolly records that he had worked with Beverley Shenstone, formerly from Supermarine, on the light alloys investigation. Subsequently he described his own appointment as 'personal advisor to Hennessy on production matters and to prepare the programme for the rest of the Beaverbrook régime'. He recalls also some events that were seen subsequently to have been of strategic significance - the manner in which the de Havilland Mosquito was included in the programme without full approval, and the urgent creation of the Avro Lancaster out of the failing Manchester bomber, matters to which further reference is made below. From his own personal acquaintance with these, he adds that 'There is no question that had the machine of decision-making been constituted as it was in 1939, we would never have seen either type' [(12)].

8.3 The 'Hennessy' target

Under the Air Ministry, the policy for forming production programmes had been that the figures should be the best estimates that could be made at the time for the greatest output of which the industry would be capable throughout the specified period. They would be used to guide the allocation of orders to the manufacturers and their sub-contractors, and to make provision for the necessary work-space, tooling, raw materials and the many ancillary elements, some of which were outlined in their earlier stages in Section 4.1. But they had not been intended to be issued to contractors as targets.

In the autumn of 1940 a new production programme was prepared, named later as the 'Hennessy' target. By this time Craven had returned to Vickers, and in effect Hennessy had sole charge of the production and planning directorates. Figure 13 provides a convenient illustration of the progress of official programmes and the actual production of aircraft throughout the years of the war [(55)]. The trend of output generally followed the programmes, as would be expected, since the maximum output estimated by the planners included feedback from the manufacturers as to what was possible with the facilities available at the time. But the 'Hennessy' target is seen to depart considerably from the general progress of production. It is widely reported that Beaverbrook thought that industry should be given targets to aim at, and insisted on the programme figures being inflated to provide an incentive to the manufacturers to make greater efforts. Writing as an 'insider', Sir Alec Cairncross confirms that this point of view had been discussed at length in Air Ministry times, but it had always been concluded that programme details should be for internal use only, and any incentives should be in the form of arrangements for bonus payments written into the contract when an order was placed [(54)]. Where a particular contractor was able to complete an order ahead of the scheduled time, this should be investigated to see if there were general lessons that could be disseminated to the industry as a whole as an improvement in best practice.

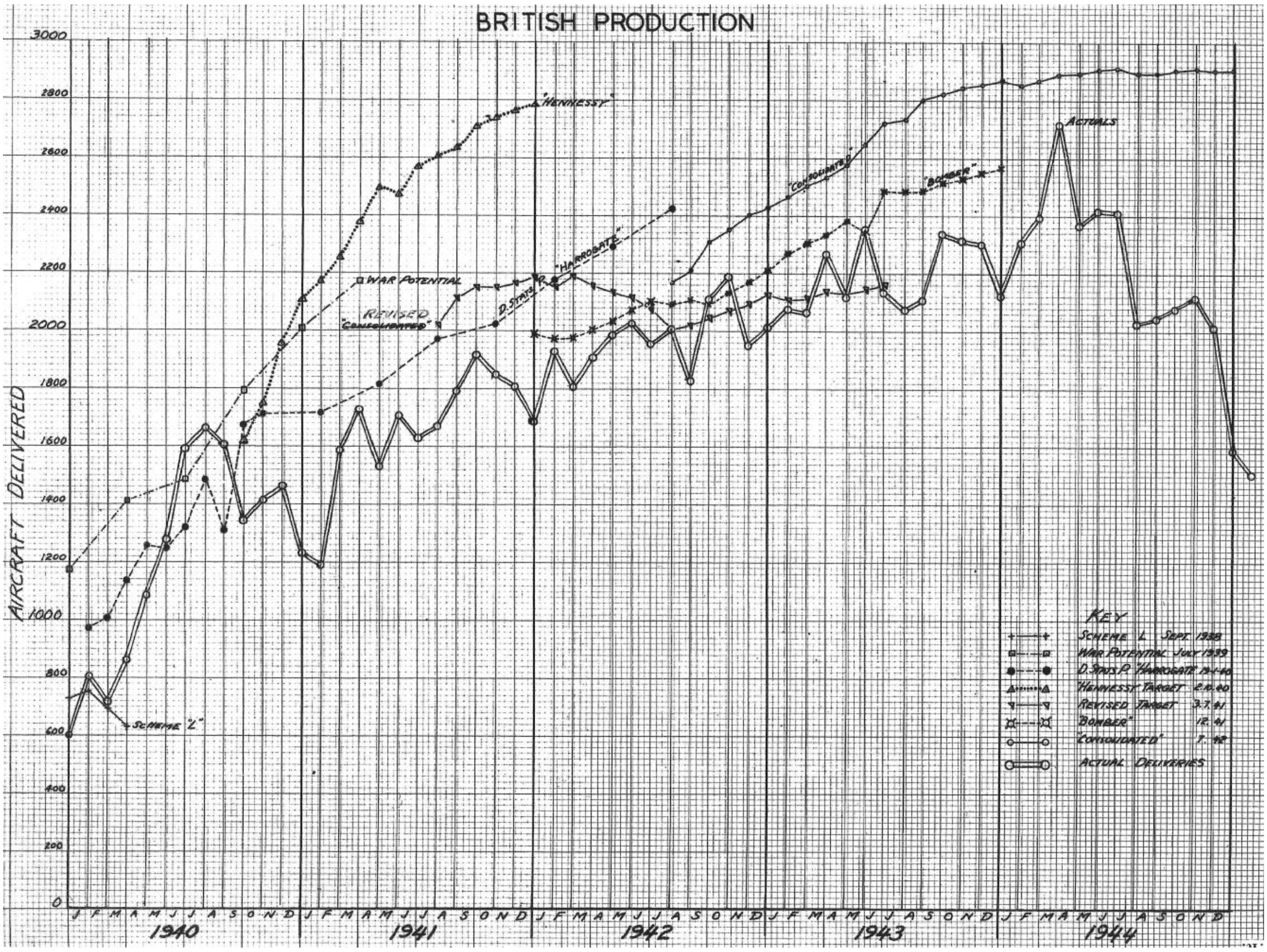

Figure 13. MAP airframe programme and industry total output, 1940 – 44
Connolly, J V (reference 55)

In Figure 13 it is seen that the 'Hennessy' programme begins at a common point with the 'Harrogate' programme as it stood in September 1940. From there, the development of the actual output continues roughly parallel with the 'Harrogate' programme projection, though it had started lower, and remained so. As indicated earlier, the steep rise in output to a local peak in July 1940 had been due mainly to the exceptional measures demanded by Beaverbrook that had bolstered RAF fighter strength when it faced superior odds in the early part of the Battle of Britain. But this was followed by a drop in output over the last part of 1940. Postan attributes that to a combination of deliveries having been brought forward to contribute to the earlier peak, and to the interruption to production by the German bombing and ground attacks during the Battle and the start of the heavy night-bombing offensive of the winter of 1940-41 [5]. The wider dispersion of production capacity undertaken as a response to this assault caused further delays, but once that had been stabilised, the general trend in output from the following spring is much as might be expected if the peak and trough of the second half of 1940 were averaged out.

The fall in output in the latter half of 1940 and its subsequent recovery could not have been anticipated in planning the 'Hennessy' programme beginning in September. But the rise in that curve is much steeper than the 'Harrogate' programme for the same period, shown as increasing from 1,600 a month to 2,600 a month over a period of 15 months. This was plainly not just an increase of 15%, the amount often quoted for a Beaverbrook 'target'. Official histories remark on the scale of this but give no convincing justification for it. Scott and Hughes merely note that it was 'more ambitious than any previously approved' [32], while Postan concluded only that it had been based on similar factors to those already established, but with the assumption that capacity was utilised to the maximum extent at all times [5].

A more probable explanation for the 'Hennessy' target being so inconsistent with contemporary programme and output figures is to be found in a memorandum he wrote for Sir Charles Craven at the end of his tour, when he was returning to Ford [56]. Included among the Connolly papers, this states that he 'had arranged for the progress planning of the American and English production to be combined so that an American provisioning programme would be issued at the same time and would indicate the equipment required for the American machines and where that equipment would be produced and whose responsibility it was'. Not many deliveries from America had yet been made when this target was prepared, so their future numbers would have been the estimates shown in Figure 11 of Section 6.3. Combining those with the 'Harrogate' programme for British production would largely account for the elevated position of the 'Hennessy target' curve.

The report left for Craven by Hennessy was very comprehensive, covering the present state of supply of materials, guns and other components as well as aircraft and aero-engines. His candid firm-by-firm comments on competence in the industry, no doubt never expected to become public, provide a window for researchers interested in finer details than are required here. In his covering note, he refers to the serious effects of enemy bombing on production across the sector, which had caused many arrangements to be made that were not part of the original plan. With the understatement typical of the times, he adds 'I am afraid that this interruption may continue'.

The immediate actions of Beaverbrook and his personal team had some very important, even vital, outcomes. But it seems to have been recognised that in the longer term the effective operation of the MAP required a more systematic working environment. After just under a year as head of MAP, Beaverbrook was moved in April 1941, to become Minister of Supply, in charge of the delivery of equipment and provisions of all kinds to the armed forces, with the exception of aircraft which remained with MAP. There, with his customary vigour and unorthodoxy, he set about increasing the supply of tanks and other equipment urgently needed in the North Africa sector [5].

MAP was next headed by John Moore-Brabazon. He had been a pioneer of aviation, learning to fly in 1908 and becoming the first holder of a British pilot's licence in 1910. During WW1 he served in the RFC on the Western Front, specialising in the development of aerial photography for reconnaissance. He left the RAF in 1919 and entered Parliament, where in the inter-war years he held various positions. He had been first appointed to Churchill's War Cabinet as Minister of Transport.

New staff transferred into an enlarged MAP Planning Directorate in the autumn of 1941 included Professor John Jewkes and Ely Devons, from the Economics section of the Cabinet Offices, and Alec Cairncross who moved from the Board of Trade. Hennessy had latterly referred to his own position as that of Chief Executive. In his hand-over memorandum at the end of his tour, Hennessy referred twice to Connolly, saying that 'The programme work is centralised in Mr. Connolly, who collects the material from the various Directors, and in collaboration with Mr. W Smith of Stats. Dept. produces the facts and figures.' [56]. Showing that this coordination was already seen to be vital at this stage, he added that 'It will be necessary for all Directors General to advise the planning group of their position and proposals, and Mr. Connolly will give you a memorandum on this subject.' Regrettably, that memorandum is not included in the Connolly bequest

Moore-Brabazon's history would suggest that he would be a more comfortable fit at the MAP than his predecessor, and it is seen that in his time the development of planning procedures had been strengthened, while the structure of Directorates tended to continue generally along the lines pioneered in the Air Ministry days. In his autobiography, he describes his contribution succinctly - 'Beaverbrook had abolished the planning side of the Ministry; I restored it' [(57)].

It is indicated that the staff of D.Stats.P moved promptly after the end of the Beaverbrook era to correct the anomalous impression given by the 'Hennessy' target and to return to the convention employed in the Air Ministry. An amendment was issued immediately, lowering the figures by about 500 aircraft a month, and then later in the summer the shift was made to the more considered 'Revised' programme.

An Appendix to Postan's history gives tables of the output figures required under the various programmes and targets throughout the war [(5)]. These were kept under review continuously, and as shown in Figure 13, a programme was often succeeded by a revised one well before it had originally been intended to end. Adjustments were also made to the requirements issued to the aircraft companies to maintain maximum production when output was affected by local circumstances. These changes were of course tracked by D.Stats.P., and Connolly's papers include some tables from which it can be deduced when some of the changes took place. These tables were the basis of the complete statistical review of the production of aircraft, engines and associated components, to which reference is made later, issued by the Ministry of Supply after the end of the war.

Regrettably, Moore-Brabazon was replaced after a year, when a chance remark he made at a private function was leaked to the press. It was claimed that he had expressed the hope that the Russians and Germans, who were now at war, would destroy each other. Though a distortion of his remark, the report was considered to be unacceptable politically, as the USSR had then become an ally, and once it had been made, he had to go. He was however soon taking his place in the House of Lords as 1st Baron Brabazon of Tara, and subsequently chaired the Committee bearing his name that planned a far-sighted programme for aircraft types to serve British civil aviation after the war.

MAP was next headed for ten months by John Llewellyn and then by (Sir) Stafford Cripps until the war in Europe was ending.

8.4 Later programmes.

After being held back by the urgent requirement for fighter defence in 1940, the heavy bomber programme had been intended to provide the main instrument by which the war could be taken to the enemy. But the reorganisation of plants to produce these larger aircraft, both existing and additional facilities, proved to be very demanding so, as Hornby put it, 'the new bombers obstinately refused to appear' [(27)]. The standardisation of the design and the preparation of schedules for all manufacturing processes had to be in place before series production could begin, and for large aircraft this would inevitably require more time and space. The increase in scale required considerable changes in the floor area for construction and in new equipment for handling the larger components and heavier sub-assemblies. This included greater headroom, which entailed reconstruction of some existing assembly shops and redesign for new ones. Jigs and fixtures needed to be much bigger than before, and large tooling such as hydraulic presses and forges had to be of higher rating. The prediction by Wright that increasing aircraft weight would lead to more efficient use of man-power could not show itself until the programme had settled down. Britain was working at full stretch, and locating a sufficient intake of new workers was further held back by growing difficulties over housing and transport for them as locations became increasingly dispersed.

The next programme after the end of the Beaverbrook era was the 'Revised' plan of July 1941. As seen in Figure 13, the difficulties at the beginning of production of the heavy bombers are reflected in this, showing a distinct dip in the expected overall output during the first half of 1942 with only a gradual rise over the following 12 months. Within this, the component of medium and heavy bombers would not meet the requirements that the Air Staff reckoned would be needed to sustain the air offensive, and on hearing of that, Churchill directed that the output of these types must be raised by 3,500 over a two-year period (5).

The outcome from the planners at MAP was the 'Bomber' programme. This foresaw a steady rise in overall output through 1942, with an increasing trend in 1943, though it was at best a pragmatic compromise. There was not much more that could be done to hasten the heavy bomber output than was already in hand, so the expected dip in output during 1942 was filled by further orders for the Wellington medium bomber. An increase in output of this type was more straightforward, as it had already been in full production for several years, and every aspect of that was firmly established. It was not exactly a stop-gap either, for the Wellington was a very effective bomber in its class, and had gained a reputation for returning from operations having absorbed combat damage that would have brought down types having a more conventional structural form. But it could not fully substitute for the greater bomb loads required at ranges beyond Berlin and for targets in Italy for which heavy bombers were now needed.

The Short Stirling was the only heavy bomber designed to the original specification B.12/36 to reach production, but that was interrupted by the necessity of dispersion following heavy enemy bombing of the Company's plant in Kent. Eventually, component manufacture and assembly would take place at 20 different sites. Shorts had to manage this alongside its production of another heavy type, the Sunderland flying boat, and as many common components as possible were used. The Stirling became operational in January 1941, and although it had a lower service ceiling than the other large bombers, it carried its due share of the strategic offensive. In the later years it was employed in other roles, and was notable in the towing of heavy gliders on and after D-day. The total built was about 2,400.

Handley Page had adapted its design of a medium bomber to P.13/36 to have four engines to meet the requirements for the heavy bomber, and in that form it became the Halifax. Beginning operations in March 1941, it passed through several developments, mostly fitted with different marks of Bristol engines. It remained in service to the end of the war, with over 6,000 being built. The Avro Lancaster was a derivative of the Manchester medium bomber, also redesigned to the B.12/36 specification but with four Merlin engines. As this took place after the Manchester had gone into production, the Lancaster was the last of the heavies to appear, entering operations in March 1942. A major addition to Bomber Command's strategic bombing force for the rest of the war, it gained the status of a national icon, along with the Spitfire for fighters. The total of Lancasters built was nearly 7,400.

The first of the de Havilland Mosquitos also appeared early in 1941, initially for reconnaissance and then as a light bomber. It had a wooden structure and avoided the weight of any armament at first, so that with twin Merlin engines it was faster than contemporary fighters. According to Connolly, the B.1/40 contract for the prototype was followed only by a technical development contract, and with the start of MAP, he had been sent with H G Bloss (then responsible for fighter production) to assess the prospects for the project. Following their favourable report, an order was placed for only 50 airframes, as the Air Staff were not persuaded of its value, in accordance with its view that bombers must carry full defensive armament [12]. Thereafter, batches of 50 were ordered on the personal authority of Freeman, despite repeated instructions from the Air Ministry to delete it from the programme. In time it was habilitated, becoming one of the most famous RAF types developed during the war. Britain had been well served by experts in the uses of timber, from merchants to carpenters, joiners and cabinet makers, and they had been largely recruited into firms making trainer aircraft. The parent firm de Havilland was one of those, and then became the lead contractor for a group producing the Mosquito, including a shadow factory originally intended for production of Halifaxes. Manufacture of components up to fuselages, wings and empennages was dispersed to firms formerly in the furniture industry, and some of the final assembly was undertaken at aircraft companies like Airspeed and Percival which also had experience in building trainers. The total of all marks of Mosquito produced in Britain during the war was nearly 7,000, and it was also built in Canada and Australia.

Now having central authority for planning across the whole aircraft industry, the MAP had to recognise any forthcoming availability of capacity and move production into that in a timely manner. One example was in connection with the Westland Whirlwind, a single-seat twin-engine heavy fighter. It went into production in 1940, and being armed with four 20mm cannons it was very effective against ground and naval targets. But an unresolved problem with its altitude performance restricted orders for it and production of Spitfires was organised to utilise spare capacity at the company's Yeovil plant, eventually totalling around 600 of the type. On the other hand, the plants of the Bristol Aeroplane Company group were kept in continuous production by three types of its own design, the Blenheim, Beaufort and Beaufighter, that moved through the shops in sequence, also benefiting along the way from the use of parts in common, and being powered by engines built by the same company (see Figure 7).

Additions and modifications were required to aircraft production plants throughout the war, but something of a pattern emerged in their arrangement, seemingly from experience rather than from an overall plan. For most of the leading types the majority came from just two factories [27, 29]. Sometimes these were both under the management of the firm responsible for the design, for others one would be a shadow or agency factory specifically provided for the purpose. Their output was augmented by construction at other sites as capacity became available. The policy of dispersal applied just as much to heavy bomber production as to fighters, but there were usually three main centres for those types, perhaps because their physical size did not lend itself so readily for sub-assembly in smaller premises.

The output of earlier types was phased out as new ones came into use during the second half of WW2. Although some capacity was added, the industry had by then effectively settled into a regime of production that required continuing evolution rather than major technological change, until the entry of the first jet-propelled types. Smoother operation was assisted by the greater oversight of raw and processed materials supply by the MAP Materials Directorate, increasingly influential from 1942. As more experience was gained, the planners could supplement the information that they had on resources at a given plant with allowances for contingencies affecting the availability of labour, such as leave, sickness and absenteeism [5]. It could also be recognised that there were persistent variations in output between firms that reflected differences in managerial efficiency and endurance. The Production Efficiency Board, set up by MAP in 1943 and chaired by a former head of the SBAC, developed ways of addressing those with what Postan called 'discreet achievement' [5].

With growing experience by management and workforce, production continued to grow to a peak in the summer of 1944, after which manpower allocations began to be diverted to support the liberation of Europe and preparations for the end of hostilities, which required a programme of reconstruction. Accordingly, in the sections that follow the emphasis is on some of the practices that had been developed in the planning of production, rather than on detail of the types and programmes introduced in the later phase of the war.

9. Steps in programme planning

9.1 The overall picture

With so many plants in action and types under construction, it is inevitable that the monthly totals would show fluctuations, as in Figure 13, but the overall trend of output from 1939 follows a clear upward pattern, gradually diminishing in rate to its peak. However, the total number of all types of aircraft produced is not necessarily the most appropriate measure of output. In a combative situation, operational requirements for basic performance characteristics are bound to increase, so as to match or exceed any gains on the part of the enemy. This is likely to result in a progressive rise in weight, even for different marks of the same type. For example, the Spitfire Mk XIV of 1944 was nearly 50% heavier than the Mk I of 1939. When the next generation of fighters, the Hawker Typhoon and the Tempest, came into production in 1941 and 1943 respectively, further additions to plant and the labour force became necessary to meet the requirements of greater machine time and man-hours resulting from their extra weight and complexity. Then the arrival of the heavy bombers increased the trend in average structure weight of all aircraft produced, which more than doubled between 1939 and 1944 [27].

A case could therefore be made for adopting the airframe weight per month as a standard measure of production, since by reflecting the sizes of the aircraft that should more fairly represent the efficiency of the use of manpower than just the number. Figure 14 shows how the half-yearly average values of both quantities built up over time, to the peak in the spring of 1944. The two plots have a quite different shape, with opposite curvature. But the use of airframe weight as a measure

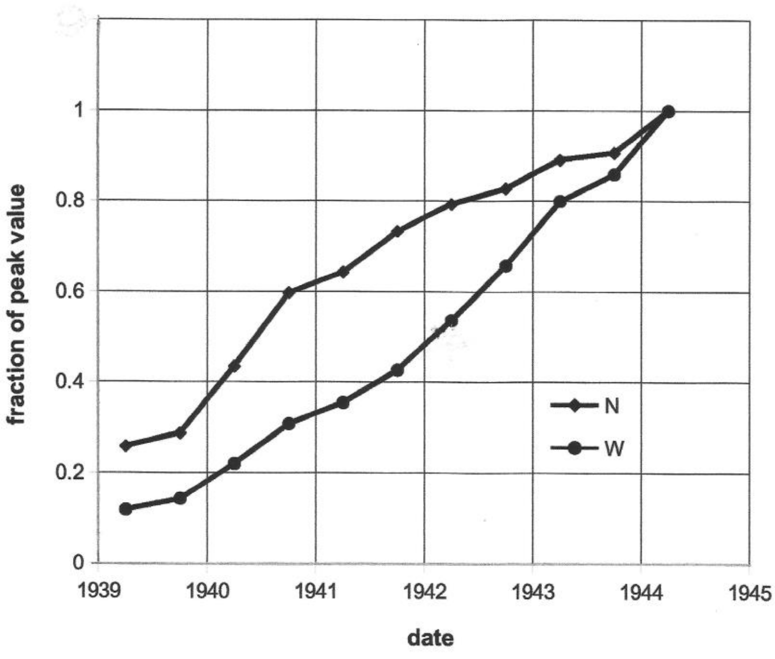

Figure 14. Comparison of the growth of airframe output by number (N) and weight (W)
Connolly, J V (reference 55)

would be subject to its own qualifications. If Wright's suggestion that the man-hours employed in airframe manufacture were proportional to $W^{2/3}$, labour would be used distinctly more efficiently in building bombers than say, trainers. But an overall output figure in numbers delivered was probably easier to comprehend than structure weight for general purposes. The RAF and FAA would keep a close watch on numbers in each type, in relation to operational requirements that would be continually changing, and in turn that would be reflected in the planning of programmes as one succeeded another. For present purposes it will be sufficient to continue here with the plot of Figure 13, which by comparing the overall output of aircraft in numbers with the corresponding figures from the programmes forms a convenient aide memoire on the unfolding of British aircraft planning and production in WW2.

The plots in Figure 13 are the totals for all classes of aircraft. Contributions to the official war history include Tables and Appendices giving the sub-totals for each of the contributing classes [5, 27, 32]. Further, a complete record for each aircraft type in production from 1939 to 1945 is given in the final MAP Statistical Review, published in 1946 **(58)**. This provides a breakdown for every type used by the RAF and FAA, covering the airframes, engines, armament, accessories and spares, with details of the raw material usage and labour employed. A precursor of this compendium is among the papers of the Connolly bequest **(59)**. This is a box of large sheets, of which a set of nine, dated 1939 and giving the programme envisaged for the years 1940 - 1942, bears his name, and have ragged edges showing that they must have been in frequent use. A replica of one page from the collection is shown in Figure 15, labelled Most Secret, the highest British security classification of the time. These papers provide a rich opportunity for researchers requiring reference to original sources.

9.2 Planning of output

9.2.1 Organising a programme

A new production programme would be based on a composite of the records of outputs from orders that had been placed already, together with the new requirements and best estimates that could be reached of the provisions needed for future orders that were under discussion but not yet issued. The planning at the Air Ministry and MAP would involve working out how closely this composite could be matched by distributing the current and potential future orders where there was suitable capacity and experience to complete them effectively. Any deficiencies would show where providing new capacity and resources would have to be considered.

The raw material for the planning of programmes included the records of workspace, equipment and manpower available to the Ministry for plants of every size and type, with information on its present utilisation. To this were added the detailed data for the progress of manufacture and construction returned on a regular basis by the companies, compiled from the time-schedules that formed a necessary part of their own documentation, as outlined previously. Increasingly, attention was needed to the contribution of subcontractors, though because of its extent this sector could not be monitored as intensively as the main plants.

Continual examination was required to ensure that the planned output could be delivered with these resources being worked to their maximum capacity. The uncertainty of forward projections meant that the programme figures would become increasingly speculative over time, due to the operation of many factors, including those resulting from adjustments to policy dictated by the course of the war and contingencies such as the dispersal of construction to reduce the effects of enemy action.

PROVISIONING AIRCRAFT PROGRAMME 1940 – 1942 MOST SECRET

(December 1939 Assessment)

AIRCRAFT	APPENDIX "A" NUMBER	Aircraft delivered to 31st Dec.1939	PLANNED DELIVERY OF AIRCRAFT																													Total Jan.1940 to June 1942
			1940												1941												1942					
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	
BOMBERS																																	
Battle	1033	1484	80	50	25	5	-	-	-	-	-	-	5	50	19	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	234
Blenheim I	967	1132	18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	18
" IF	934																																
" IV	959	497	77	105	125	145	145	145	145	108	145	145	145	132	145	145	140	128	120	120	120	90	120	120	120	110	120	120	120	120	120	120	3760
Hampden I	1001	343	35	35	33	36	28	19	16	17	18	20	22	20	25	25	25	25	25	25	25	20	12										507
" II	1017																																
Hereford	953	25	15	15	20	20	20	20	15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	125
Whitley I	813	34	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
" II	993	46	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
" III	1012	80	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
" IV	1004	33	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
" IV(a)	-	7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
" V	1022	86	22	23	24	26	26	27	28	21	29	30	30	25	30	20	15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	376
Albemarle	935	-	-	-	-	-	-	1	2	6	12	20	28	36	44	50	54	59	62	63	70	67	84	92	108	112	130	144	161	180	190	200	1975
Wellington I	1056	182	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1
" I(a)	1020	119	34	10	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	49
" I(c)	1047	-	-	27	34	43	47	51	56	50	70	78	76	68	80	74	73	66	54	47	42	15	7	-	-	-	-	-	-	-	-	-	1058
" III	952	-	-	-	-	-	-	-	-	-	-	1	2	4	6	15	25	40	55	70	84	90	150	146	148	146	158	164	169	174	180	185	1992
Manchester	944	-	-	1	1	2	2	3	5	7	10	15	20	24	31	38	48	58	68	80	91	80	104	112	116	110	124	126	127	128	128	128	1787
Stirling	1009	-	-	1	2	3	3	4	7	7	15	21	25	29	39	43	46	52	53	55	57	43	57	59	59	49	59	59	59	59	59	59	1083
Halifax	1024	-	-	-	-	-	1	3	4	6	6	6	8	10	10	12	12	16	18	18	19	24	38	40	48	52	64	68	74	76	92	100	825
		4068	282	268	259	280	272	273	278	222	305	336	361	398	429	422	438	444	455	478	508	429	552	569	599	579	655	681	710	737	769	792	13790
FIGHTERS																																	
Gladiator		364	14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	14
Defiant		16	6	14	19	28	38	40	48	40	60	60	60	50	50	45	35	25	10	6	-	-	-	-	-	-	-	-	-	-	-	-	634
Hurricane		785	95	106	124	130	130	140	150	120	170	180	180	165	180	170	170	140	120	95	62	10	-	-	-	-	-	-	-	-	-	-	2637
Tornado		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	76	84	101	88	116	78	-	-	-	-	-	-	-	-	543
Typhoon		-	-	-	-	-	-	-	-	-	-	6	10	16	28	36	46	60	-	-	-	-	-	52	149	141	166	183	186	190	213	218	1700
Spitfire I		479	44	50	55	60	65	68	70	55	15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	481
" II		-	-	-	-	1	9	18	25	33	41	50	60	60	75	80	90	100	115	130	150	100	150	150	150	150	150	150	150	150	150	150	2617
" III		-	-	-	-	-	-	-	-	-	57	75	75	70	80	80	85	90	38	-	-	-	-	-	-	-	-	-	-	-	-	-	850
" (Griffon)		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	52	95	100	75	100	100	100	90	100	100	100	100	100	100	1312
Beaufighter		-	1	1	3	8	12	18	24	24	35	40	48	42	67	75	81	101	109	118	127	105	145	160	176	173	205	206	188	210	229	236	2967
Whirlwind		-	-	-	2	4	6	8	12	10	16	16	16	14	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	114
		1644	160	171	205	231	261	292	329	282	392	427	449	417	490	486	507	516	520	528	540	378	511	540	575	534	621	639	624	630	698	704	13669
Swordfish		469	3	-	-	-	-	-	-	-	-	-	-	2	5	10	17	23	30	35	40	30	40	40	40	35	40	15	-	-	-	-	403
Roc		81	12	12	12	12	7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	55
Proctor		12	12	15	20	20	20	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	88
Walrus		184	8	8	8	8	9	10	12	9	12	13	14	14	18	19	21	22	24	26	21	28	28	28	28	24	28	28	28	28	28	28	580
Fulmar		-	1	3	6	10	13	17	20	18	25	27	27	22	27	27	27	27	22	18	15	13	11	10	10	10	10	10	10	10	4	-	450
Albacore		-	5	6	10	12	14	19	22	19	30	33	36	35	43	43	43	43	43	43	43	30	43	43	43	38	43	43	43	43	43	43	997
Barracuda		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	3	6	10	12	14	17	18	19	20	20	20	181
		746	41	44	56	62	63	47	54	46	67	73	77	73	93	99	108	115	119	122	128	97	128	131	133	121	138	112	100	101	95	91	2734

Figure 15 Example of detailed airframe production programme, 1940 – 42 Connolly, J V (reference 59)

Others arose from problems in the maintenance of supplies and manpower, in the construction of agency buildings, and changes in plant and procedures that the companies had been planning themselves. One result was that programmes would need frequent adjustment and would rarely extend as far as two years. A given programme was usually succeeded by another well before its nominal period had elapsed.

As reviewed in Section 5.2, the first time that the system as a whole was addressed was in 1939 when Lemon and his staff were trying to bring some reality to the expectations for the output under Scheme L. With the pressures of the time, there was no possibility of establishing a theoretical basis for the dynamics of an aircraft production system, the modelling of the practices of operatives who were working it, and of its supply chain, which would become part of the subject of production engineering after the war. The process employed by D.Stats.P. was to look for correlations between output and the factors that were thought to be the most influential for it. These would then be expressed in graphical form, and increasingly represented by empirical mathematical expressions which could be projected forwards on the assumption that they would continue to apply in the short term. As the war progressed, more factors could be included in the correlations, such as the effects of improvements in the tooling employed and in the design of jigs and fixtures.

9.2.2 Planning procedure

Considering the magnitude of the task, little of the detail of the planning of the wartime production programmes has been reviewed in the literature. The most useful sources generally available are the books by Ely Devons [(60)] and Alec (later Sir Alec) Cairncross [(54)], who had been brought in to MAP in 1941 (see Section 7.3) and participated in much of the subsequent development. It is unfortunate that Lewis Ord left no record of the earliest stages of this work, overseen by Lemon. He was later seconded to give advice on aircraft production to the Australian government and then as general manager of Canadian Associated Aircraft Ltd. His book of 1944 was basically a warning that the position of British industry after the war would be precarious unless it brought about a significant increase in productivity [(61)].

Writing in 1950, Devons is at pains to emphasise that the process of programme planning had been an evolutionary one. It was not a straightforward linear procedure, in which the Air Ministry and Admiralty service directorates could decide the types and numbers of aircraft the squadrons would need and the MAP directorates could decide which firms were suitably placed to receive and carry out the orders to produce them. It was instead a process of continual development, which involved ongoing interactions between at least those official groups, together with the various components of the industry and other Ministries responsible for managing the supplies of raw materials and labour. The outcome of these interactions would be a combination of many compromises among multiple options. But the room for manoeuvre was limited in all directions, so that a programme that could be implemented was usually a modest evolution from the current one.

A critical element requiring careful management was the interaction of MAP with industry, as reported above. The decision had been taken not to nationalise it, so the component firms were still private companies. In wartime, the MAP was empowered to give directions, but cooperation was essential and this could not be heavy-handed. Occasions would arise when serious failures of management caused the Ministry to step in and order substantial changes to procedures and even replacement of personnel, but having regard to the scale of operation reached, they were not common.

Overall, the British industry was fully committed to the defeat of the enemy, and was for the most part inventive and resourceful. For the possible implementation of some new technical development, it could call at any time for evaluation by the R & D departments at the RAE and NPL. A special wartime patents agreement allowed for the protection of any new intellectual property that emerged.

Devons and others wrote of the need to be aware of a tendency of companies to underestimate the time that would be taken to reach various stages in production. There would be few problems with the continuation of an existing contract for a given type and mark of aircraft, but bringing a new mark into production invariably involved a host of modifications, and the firm's estimate of times for that would usually be problematic. The greatest uncertainty was for beginning the production of a new type. The MAP staff could call on data from previous cases to justify a reassessment of estimates that seemed too optimistic, and generally the matter could be resolved without having to go to higher authority. There was a realistic acceptance that firms would inevitably try to present the data that they were required to produce in forms that would put them in the best possible light.

The output data most quoted were for airframe production, and planning had to ensure the availability, at the right times and in the right quantities, of the multitude of small parts required during assembly - rivets, screws and other fasteners, hinges, latches and very many more. For an airframe to become a service aircraft it had to be fitted with numerous other components, that were mostly incorporated into the airframe as its construction proceeded - the electrical, hydraulic and pneumatic systems, fuel tanks, radiators, oil coolers and pipework, oxygen supply and so on. Others usually incorporated at a late stage in the construction were the engines, propellers and constant-speed units, undercarriages, turrets, radio and radar equipment etc., for which there were independent suppliers with substantial plants and shadow factories in their own right. At first, the production directorates responsible for overseeing this ancillary supply did not formulate programmes, but worked with forecasts that looked only 3 months ahead. Devons reports that they were persuaded to set up data collection procedures and draw up programmes in coordination with the planning directorate. The first of these was for aero-engines, and within a short time they also covered complete power plants, radiators, carburettors and magnetos; propellers, constant-speed units and spinners; undercarriages, wheels and tyres; aircraft armaments and bombs; and certain items of radio equipment. For D.Stats.P. to construct an appropriate plan for an airframe, the programmes for all the various contributors would have to be coordinated with it.

A further element of production, often overlooked but emphasised by Devons, was the provision of spares. Contracts required the manufacturers to include these on a given scale from a few key components up to all the parts for complete airframes and engines. Initially, these had been based on standard ratios, but this led to surpluses and shortages, and there was a shift towards reference to the whole picture of the provision and usage of spares. For this, there had to be reliance on returns from the squadrons, MUs and the CRO that were necessarily retrospective, and from supplies to and withdrawals from stores. For many reasons, the data were incomplete and generally unreliable, something which the MAP never managed to rectify fully [(60)].

As well as the need for mutual respect, if not trust, between personnel from the MAP and from industry, it was also necessary to foster trust within and between the directorates. It was accepted that staff could give their best only if they felt that they understood the setting within which their individual contributions were made. A policy of openness was adopted, exemplified by the Chart Room at MAP, where diagrams illustrating the present state of programmes and early outlines of proposed new ones were on view with firm-by-firm contributions for all to see, and constantly brought up to date. It was appreciated that graphs and charts were superior to any number of tables of figures for this purpose. To facilitate a rapid understanding of what a chart was showing, there was a preference that not more than two lines should be included - these were usually one each for the relevant plan and the corresponding output.

Cairncross did not commit to print until 50 years later, though he states that in doing so he worked from the notes that he made at the time [54]. At first, he is scathing about the methods of programme planning developed before his arrival, asserting that it was not something that should be handed over to 'technical experts who would work out machine-loadings, man-hour requirements, structure weight and all the other incunabula' and he was dismissive of 'those who hankered after a more 'scientific' programme indicating what the labour and equipment in each factory *ought* to be capable of producing'. He seems not to have wondered how the people who did this, in industry as well as at MAP, had managed to plan programmes and get the corresponding aircraft deliveries up to more than 1,800 a month by the time that he joined them. But later in his book he is found insisting that 'the normal curve of output, and therefore of a good production programme, is shaped like a logistic curve, flattening out at peak', so that with experience he appears to have changed his views substantially.

The emphasis in his account is on the coordination role adopted by the planning directorate, covering much the same ground as Devons, whose book he cites frequently and to whom his own book is dedicated.

From around 1942 onwards, the shortage of labour became a limiting factor in how much further the rate of output could be raised. When a new programme had been agreed, an application had to be made to the Ministry of Labour for an allocation of any additional manpower required. The provision granted was invariably lower than that requested. In one instance given by Cairncross, the application for the year 1943 had been for 360,000 additional workers, but the eventual allocation was 160,000. As well as trimming the programme accordingly, the MAP planners had to relocate work to areas in Britain where they were told that labour was most likely to be found. The Minister, Ernest Bevin, had heard that the productivity of aircraft plants in the US was twice that for British industry, and reckoned that putting a tight rein on allocation would lead to better management and improvement in industrial efficiency.

Although there is not sufficient detail on record to illustrate fully the material used at D.Stats.P in the formulation of requirements for production, some examples follow of the type of correlations investigated, principally arising from reports and notes left by Connolly.

9.2.3 Elapsed time to entry into service

One of the estimates that the MAP planners had to make was of the likely elapsed time from the start of an aircraft project to the entry of the type into service. It was noted earlier that this had been a cause of concern throughout the 1930s [24, 45]. At first the only data were for types that were specified at that time and, even in the period of rearmament, they had been designed and prepared for production in very different circumstances from those that would arise in wartime. Moreover, the number of cases in any category (fighter, bomber, etc) was still too small to provide much clear guidance.
For the assessment it was necessary to have a clearly-defined starting-point for the process, and although the conception and preliminary design work at the firm would have preceded it, the point chosen was the date of the Advisory Design Conference, where the concept was first discussed in

detail between the manufacturer and the Air Ministry. That date was a matter of record, as was that of the final point, the delivery of the first aircraft to a squadron.

The planners had to use what was available, and the data were built up gradually for this purpose in just three categories of airframe weight: 3,000 – 7,500lb, 7,500 – 15,000lb and over 15,000lb. For each project three intermediate points were included within the elapsed time to give more information about the process and indicate where improvements would be most profitable. These were the dates of the Mock-up Conference, the first flight of the prototype and the point at which the first production aircraft left the plant.

Towards the end of the war, Connolly prepared a report on all the data that had been collected on this elapsed time [(62)]. One of the graphs from that, for airframes in the 3,000 to 7,500lb range, is reproduced in Figure 16. The longest elapsed time here is 51 months for the Beaufort (start-point April 1936) and the shortest 24 months for the Mosquito (December 1939). Though the scatter is wide, there is a certain amount of coherence in the centre of the chart. It was concluded that information of this kind was useful to planners, if it was taken in conjunction with other concurrent matters affecting the manufacturing company and the particular plant involved, as outlined above.

It seems surprising that earlier events in the life of a project, from the issue of the Specification up to the Design Conference, were not included in this presentation. As outlined in Section 3.2.3, warnings had been given in the 1930s from the industry side about unreasonable delays occurring during that period, but similar recommendations for reducing them were now resurfacing a decade later, in much more critical circumstances. On the basis of wartime experience, Eric Mensforth and William Petter pointed out that since the overall purpose of an aircraft firm is production, these recommendations must be taken into account from the initial conception of a new type and coordinated throughout the ensuing design with the requirements for efficient production at every stage [(25)].

9.2.4 Elapsed time to peak output

A key projection required for planning was how the output of a given make and mark of aircraft from a given factory could be expected to rise, from the first delivery to the point of 'peak output', when it was working at maximum capacity. In a paper compiled later, Connolly reported that planners in the Air Ministry had noted by 1940 that the pattern of output was only weakly dependent on the type of aircraft being built and the scale of the operation [(63)]. If there had been no serious setbacks, a graph of the rate of output against time followed a similar path, reaching a value for peak output after 13 to 15 months from the first delivery. It was reported that for planning purposes, a 'rough empirical formula' had been devised to represent this. The actual formula used in 1940 has not surfaced, but some tabulated values quoted from it by Connolly are plotted in Figure 17, where for present purposes they have been fitted empirically by a third-order polynomial equation.

For practical use, curves like this were pinned up in the Chart Room and would probably have been circulated as a standard figure, from which values could routinely be read off without further calculation.

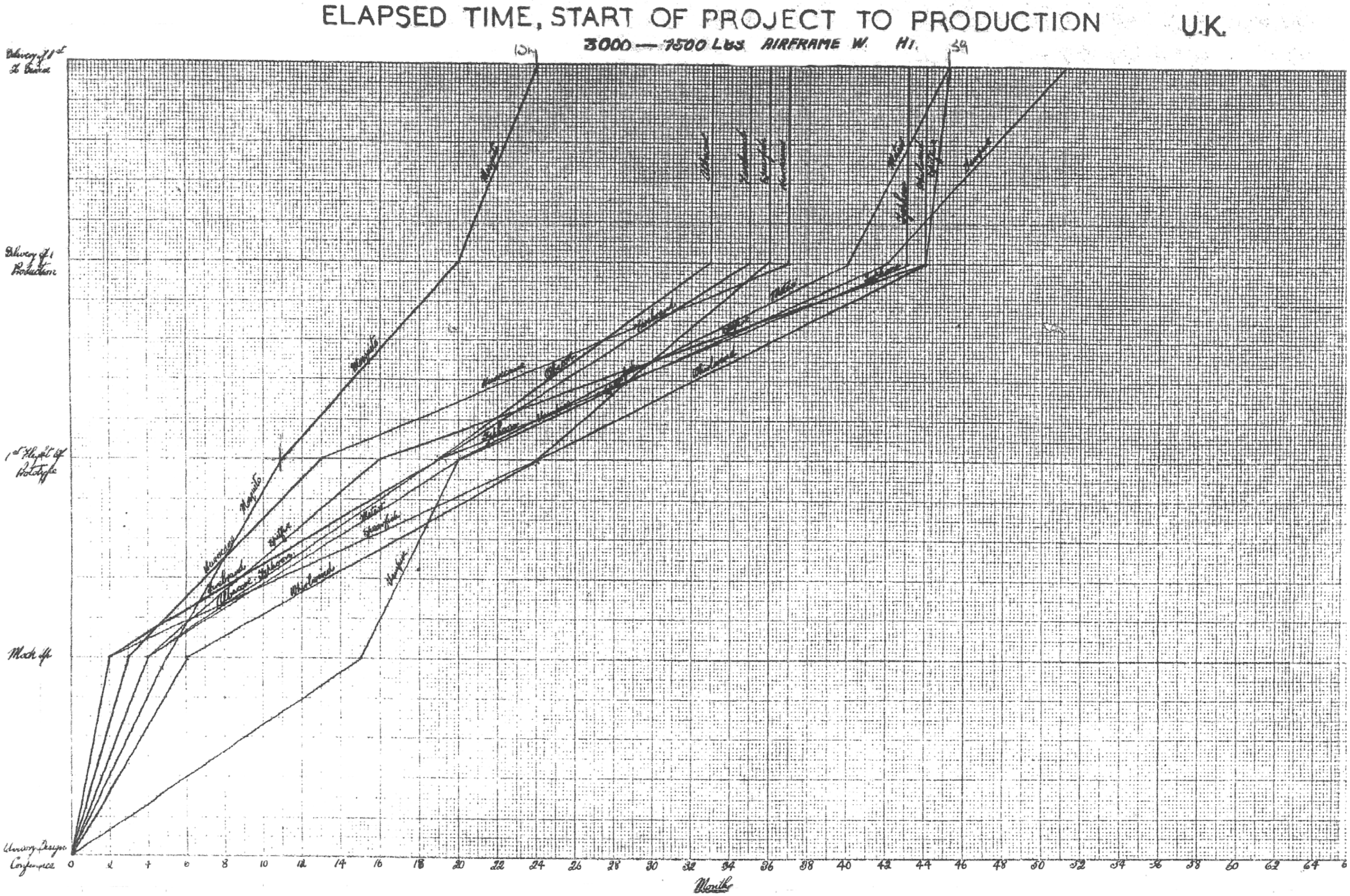

Figure 16. Elapsed time from start of project to delivery of first aircraft to user
Connolly, J V (reference 62)

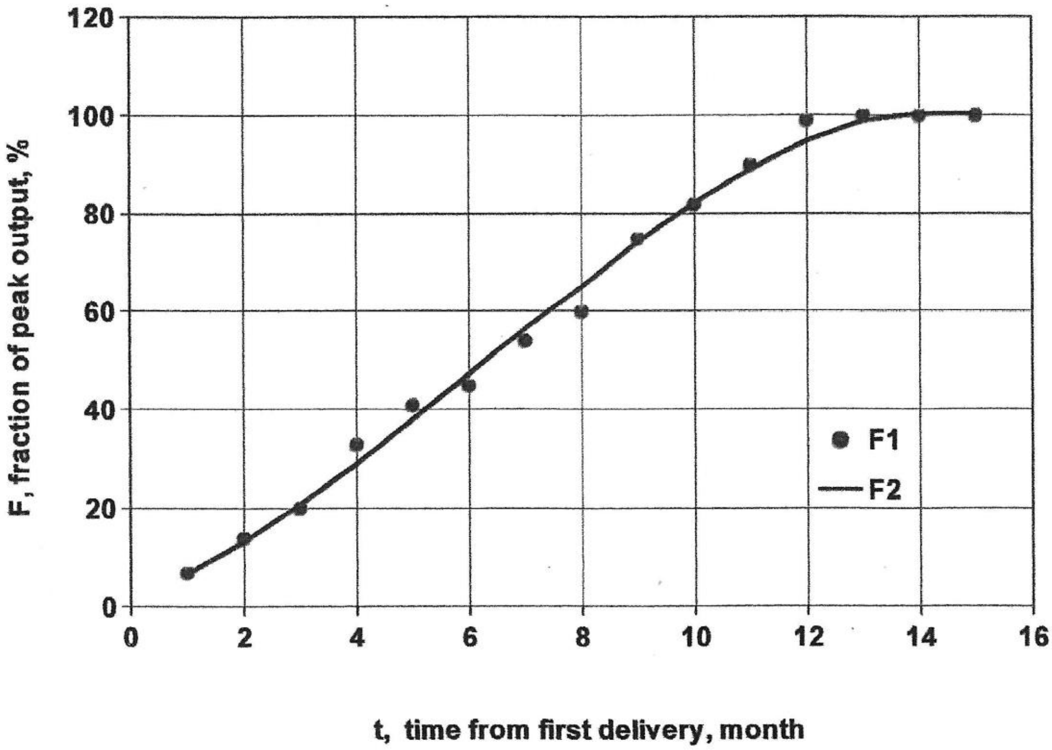

Figure 17 Rate of attainment of peak output after first delivery, 1940 figures

The general form of Figure 17 is that of a 'learning curve', in which there is a initially an accelerating build-up as the skills required for the job were being learned and practised. There is often a central part that is roughly linear, indicating a steadily improving rate of production, followed by a third stage in which maintaining that becomes progressively more difficult until the peak rate is approached, when the capacities of the facilities and the workforce are utilised to the full. In the example of Figure 17, the curvature at the two ends of the graph is relatively small, suggesting that in 1940 the data for plants that had reached peak output by then were those for firms that were already well-established, with a more experienced and flexible workforce than would be available later.

Over time, the increasing history of known output figures provided a basic framework of past achievement, which would strengthen the credibility of forward projections. Connolly revisited the representation of the time to peak output later in the war, when many more examples could be included [(63)]. A plot was prepared showing the average monthly output for 25 aircraft programmes involving 16 different types from 25 factories during the whole war period from 1939 to 1946. The structure weight of the aircraft covered varied from 2,500lb to 18,000lb, and the peak production rate from 20 per month to 160 per month, and it is said in the text that 'no special selection or rejection was exercised'. The unweighted mean monthly output values for all the cases covered are plotted in Figure 18. The full line shows the empirical fit to the data in the form finally adopted by D.Stats.P. for this kind of presentation.

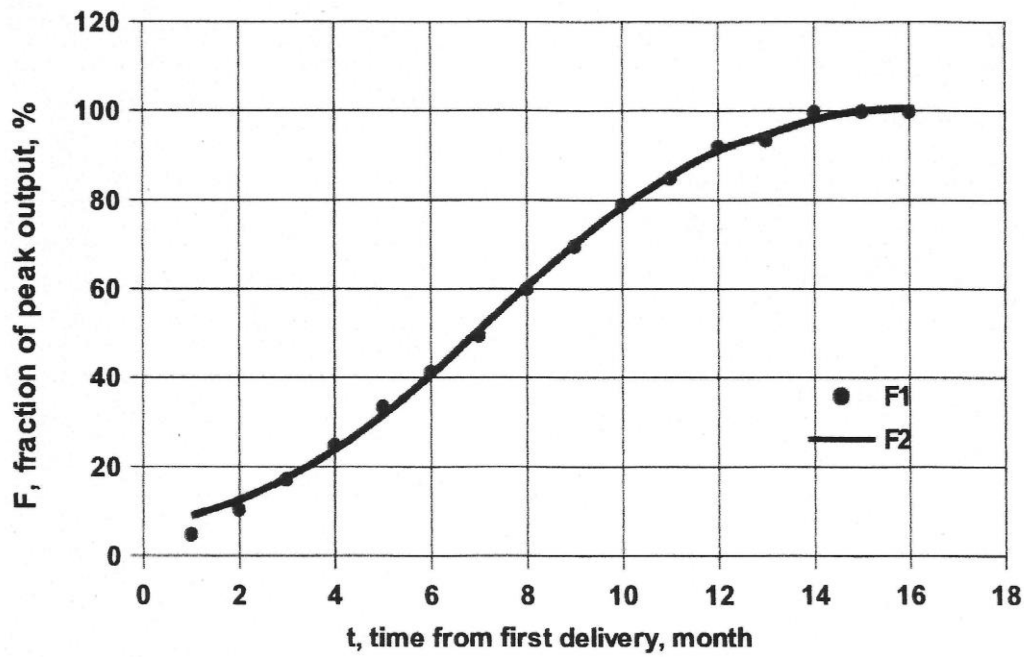

Figure 18 Rate of attainment of peak output after first delivery, examples over WW2
Data F1, standard fitted equation F2
Connolly, J V (reference 63)

The expression used was a variant of the 'logistic' formula used to represent the growth of populations by Pierre Verhulst in 1844 - 45, though similar forms had been in use earlier. It was not related in principle to the causative factors involved, but simply one that had a shape that could reasonably reflect the data being presented. The version used at the MAP gave the relation between the output per month F and time in month t in the form

$$F = K/(1 + e^{(a-bt)}) \qquad (1)$$

or

$$(F/K) = 1/(1 + e^{(a-bt)}) \qquad (2)$$

where K, a and b are positive constants chosen to obtain the best fit to the data. This particular expression seems to have been chosen largely because it had already been in use in other fields.

At a time when there were no computers or electronic calculators, finding the three constants to represent a particular set of data could be a tedious process. Though tables of exponentials were available, it was simpler to use a form that could be worked with ordinary logarithms (to base 10 rather than e). In that form, the basic expression became

$$(F/K) = 1/(1 + 10^{(a-bt)}) \qquad (3)$$

with F/K then converted to a percentage.

A curve represented by Equation (3) has the characteristic that the mid-point, where F/K = ½, the time t is given by a/b. Thus the curve is steeper, and so reaches the maximum output sooner, the greater the value of b.

As shown in the example of Figure 19, plots of this function were prepared on transparent film, which could be laid over a graph of the data drawn to the same scales, to provide an initial estimate of the constant b (in Figure 19, this is represented by B, the reciprocal 1/b, since typical values of b were less than 1, giving B values greater than 1 that were easier to visualise. This has the minor disadvantage that a desirable situation from the production point of view is one with a small value of B). The two constants K and a have been given typical fixed values in that Figure, the product of

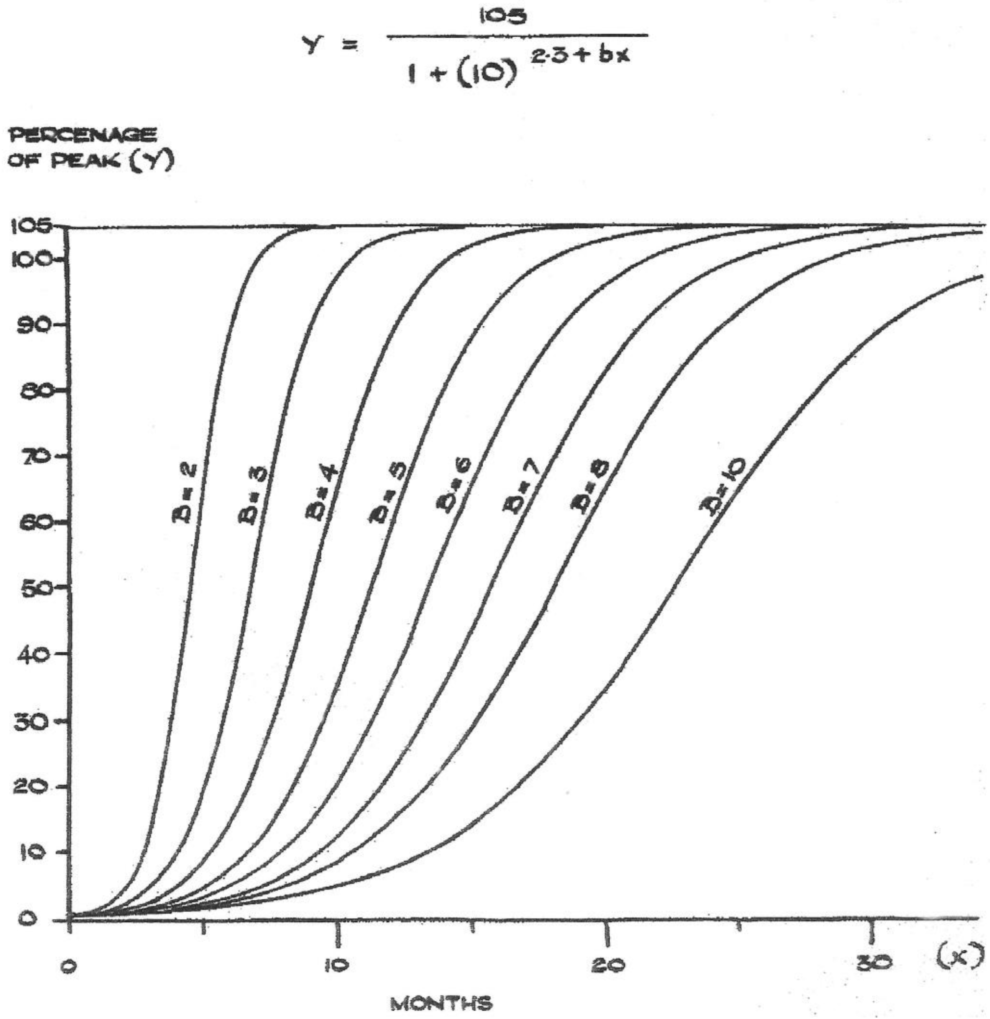

Figure 19 Generalised plot of standard fitted equation for production data
Connolly, J V (reference 63)

experience with using this approach.

Curves following Equation (3) are asymptotic to the value 1 (or 100%), but only as the time t tends to infinity. It was found by experience that a closer representation of actual data near the peak of a production curve could be obtained by taking K to be somewhat more than 100% (105 in the example of Figure 19). Although the value of 105 would not be reached for an infinite time, the remaining curvature at 100 is imperceptible. It was less important to obtain a good fit at the lower output rates, and a fixed value of 2.3 is used as the value of 'a' for all the curves shown. Changes to 'a' move the curve bodily along the t axis, so that in principle it could be chosen to make the curve pass through the actual output at t = 1 month; in practice, that was found to worsen the representation near the peak. A typical lack of fit with the data near the beginning, due to choosing a value for 'a' to improve it near the peak was seen in Figure 18.

The planners gave most attention to the parameter b, or its reciprocal B. This controls the gradient of the central part of the curve, and it came to be known as the 'growth index'. After the war Connolly was Professor of Aircraft Economics and Production at the College of Aeronautics (now Cranfield University) (64). One of his associates there, P J Stanley, published an analysis of wartime aircraft production data for Britain, the US, Germany and (some values from) Japan, using this approach (65). One figure from a collection of British production data is reproduced in Figure 20, showing a range of examples. There is clearly much variation in the degree of fit between particular cases, though often there are interruptions to output, through factors such as a change of type, or of the mark of a type, being produced. The mean value of B obtained from all the British data analysed was 5.73, compared with the (faster) growth value of 4.79 for the US. A minor consolation for British planners was that the variation of B from case to case in the data for the other countries had been even greater than for Britain.

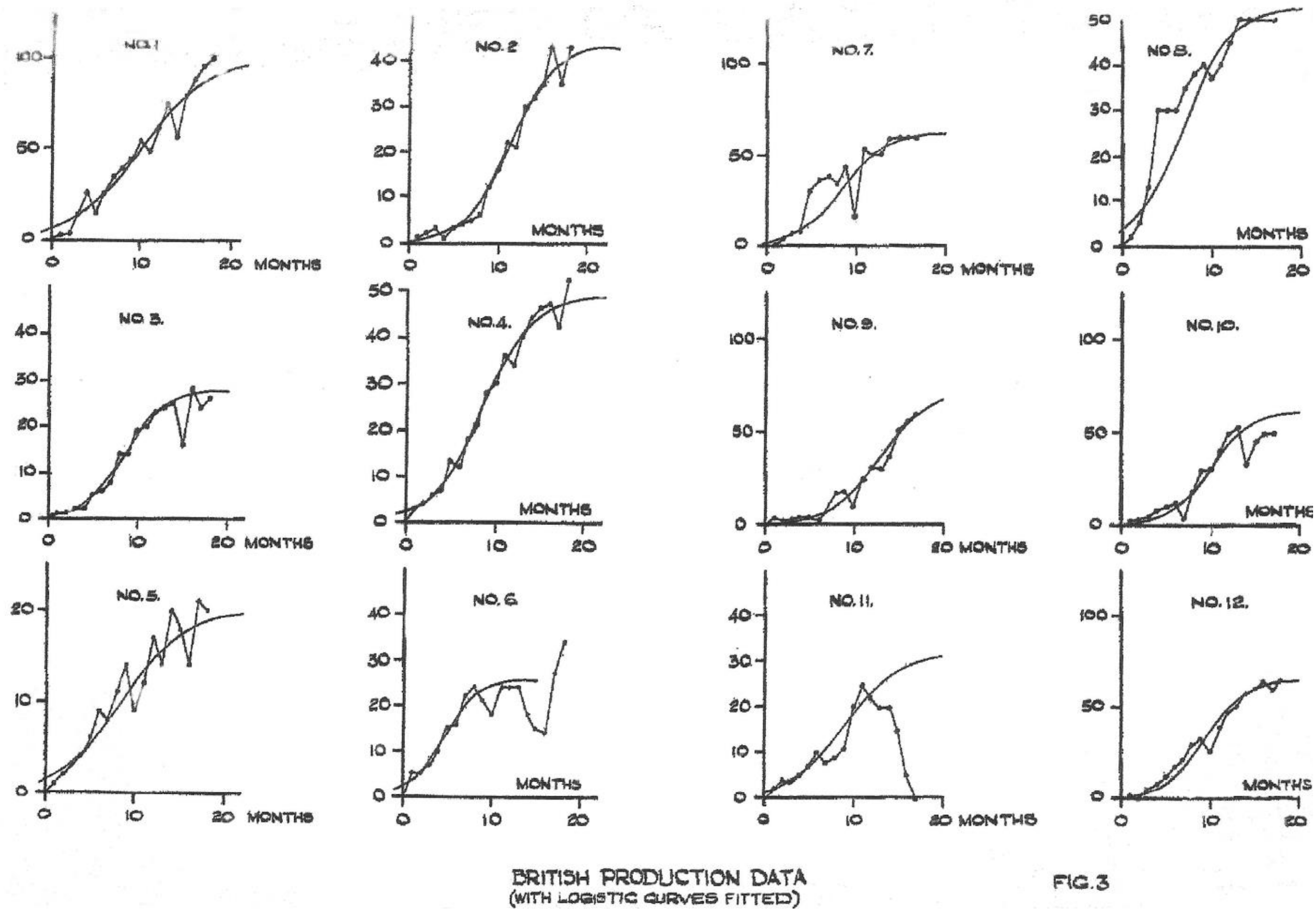

Figure 20 Variation of fit of standard equation over 12 cases
Stanley, P J (reference 65)

9.2.5 Efficiency

The graphical representation of overall time-scales for production, as in the Figures shown above, formed an essential basis for the planning of programmes throughout the war. These times were in turn dependent on many factors, and returns were obtained for progressively smaller elements of the process to refine the modelling. Inevitably, that brought attention to factors affecting efficiency in the use of equipment and man-power, as identifying opportunities for improvements in these would bear directly on the speeding-up of delivery of aircraft into service. A report by Connolly from January 1940 shows that data in support of that were gathered from the beginning of the conflict, with processes that would become known as 'time and motion studies' (66).

Figure 21 is a plot from that work, showing the total man-hours required for the construction of aircraft then in production, plotted against their structure weight, assumed to be the main governing variable. The types represented vary over a wide range of structural form, from having a fabric covering, through wooden skin to fully stressed-skin and geodetic metal constructions [the point off the scale at the top is for the Lerwick flying boat, for which it would be expected that additional work would be required due to the more complex hull form than for land-based types]. On Connolly's copy of this figure, a few further points have been pencilled in, showing estimated values for types that were in preparation, though not yet in production, which are also fairly consistent with the curve.

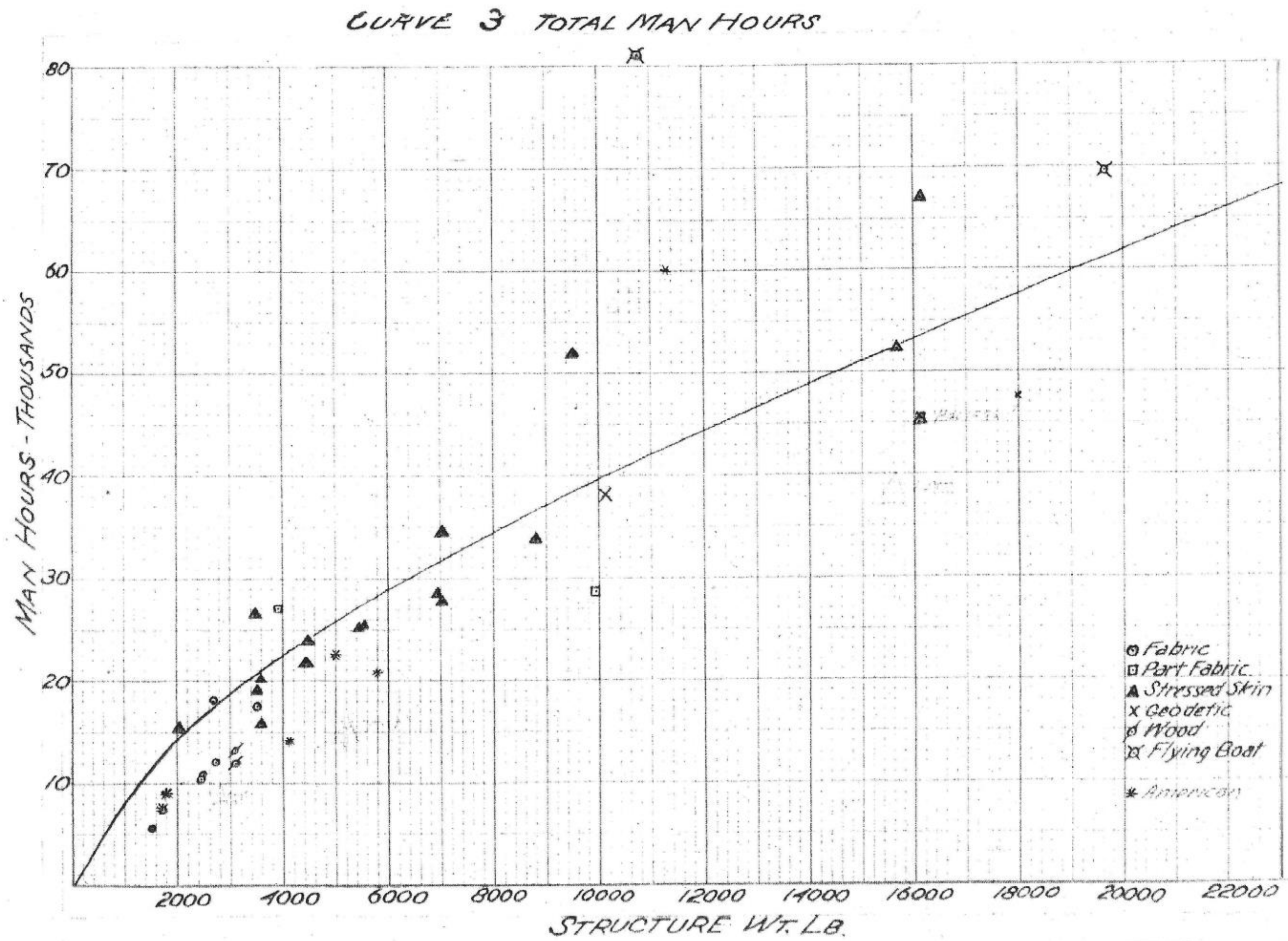

Figure 21. Total man-hours required for construction versus airframe weight. Data of 1940 Connolly, J V (reference 66)

Despite the small number of cases and the great differences of type and time, there seems to be a distinct trend with weight. The curve shown represents the judgment that man-hours would be proportional to $W^{2/3}$, as given by Wright's pre-war work [38]. In Connolly's papers is one written as a guide to Wright's methods, though regrettably, it is without its Appendices and Figures [67]. It is stated there that the British data suggested a man-hour requirement closer to proportional to $W^{3/4}$.

After the end of the war, Connolly composed a six-part series of papers on problems in aircraft production for *Aircraft Engineering* [68]. One of the illustrations for this is shown in Figure 22, which includes the percentages of peak output, weight and cost against time for production by the British and American industries from 1936 to 1944 [that the labelling of the curves for the UK and US in this Figure had been reversed was acknowledged in the next part]. The similarity of the cost and weight curves for both sets of data confirms that they are closely related.

Connolly's study of 1940 data also included values collected on the cost of providing jigs, which was seen to be varying widely in the returns given by manufacturers [66]. Reduced to cost per aircraft per month delivered, these values are shown plotted against structure weight in Figure 23, with a straight line given as a first attempt to obtain a working relationship for this factor. As might be expected for work in the Directorate with 'statistics' in its name, the line can be confirmed to be a least-squares fit. The correlation coefficient R^2 in this case is about 0.7

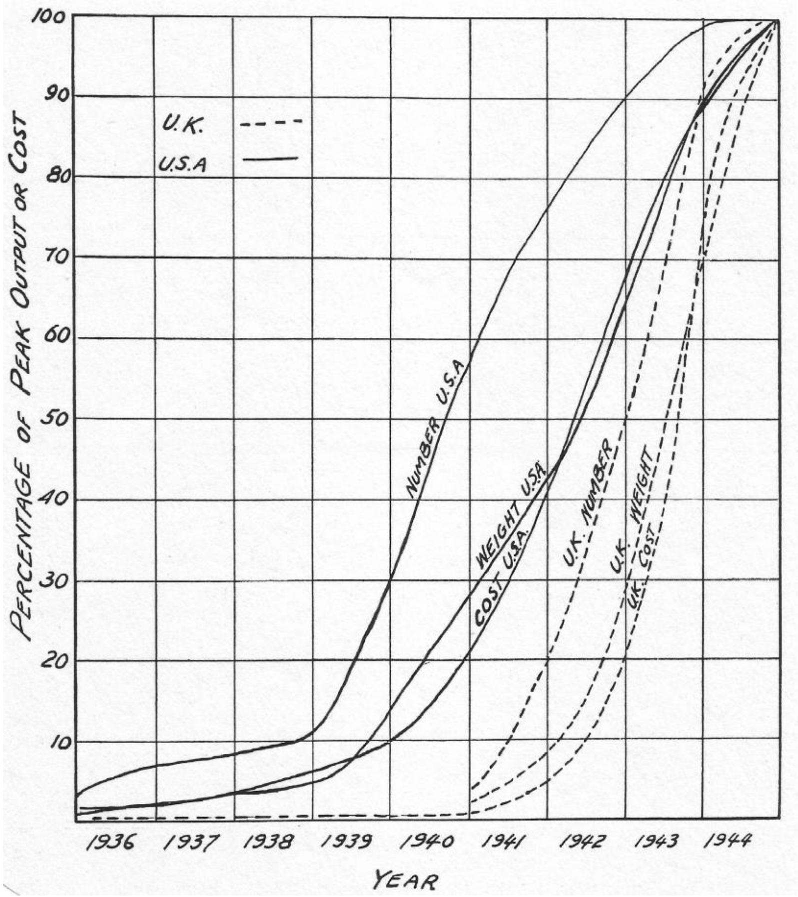

Figure 22. Output, weight and cost of airframe production by UK and US industries, 1936 – 44
Connolly, J V (reference 68)

It is clear that many attempts were made to obtain representations of this kind for factors across the whole spectrum of manufacture, though those shown here are

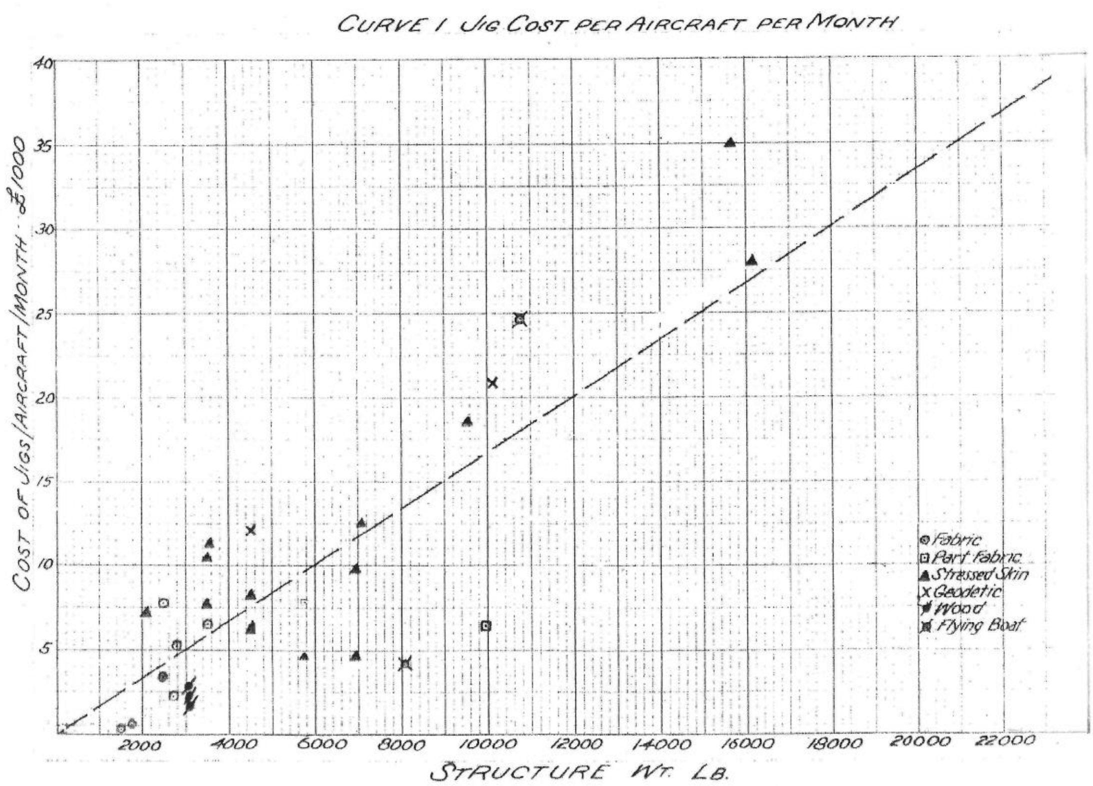

Figure 23. Jig costs per unit rate of output versus structure weight of type
Connolly, J V (reference 66)

among the very few that seem to have survived. In a contribution to the discussion on a RAeS presentation by R C Fielding in 1947, Connolly re-asserted his own conviction that curves such as these represented underlying relationships that should be considered to have a scientific foundation (69). He accepted that it was not yet possible to reduce the causes to a few 'simple components, to measure one or two definite quantities and isolate variables'. But he thought that 'if a mass of production data had been systematically recorded since the beginning of aircraft manufacture, firm relationships with primary variables could have been established, as they had been for example in aerodynamics for 'lift curves, drag curves and moment coefficients'.

10 The score

10.1 Summary

It has been recounted here how the procurement of British military aircraft was facilitated over the period up to and including WW2 by a progressive interaction between the industry and the relevant Government departments. In its early years the relationship was a conventional one between supplier and customer, but in WW1 publicly-funded capital support through provision of the National Factories and the encouragement of subcontracting were early instances of an accommodation that would continue to develop subsequently.

The new Air Ministry established in 1918 did what it could to sustain an aircraft industry through the period of national austerity that followed the war. This was done by rationing the meagre orders that could be afforded around the few companies that continued to operate, and placing others for experimental types to encourage progress in aviation technology. From the assignment in 1923 of a defined role for the RAF in homeland defence, the Ministry began issuing a sequence of Schemes for aircraft procurement, each covering a period of a few years, and issued specifications setting out the technical and operational requirements for aircraft types to meet those needs.

The first part of the 1930s was a period of major adaptation in the industry arising from conversion to the all-metal stressed-skin monoplane configuration. Accompanying confusion at the Ministry over the pace of technical development and delays in decision-making led to new types reaching the RAF being few in number and obsolete before entering service. Changes made at the Ministry to obtain a speedier procurement process included suggestions originally made from the industry side, and it was recognised that future planning would require a detailed understanding by both parties of what the industry could actually produce at a given time.

From 1936 Britain began a programme of rearmament to counter the aggressive resurgence of Germany under Hitler. This became a wide-ranging operation, continuing up to and during the war that followed. Capital was provided for enlargement of existing plants and new construction, supplemented by a revived scheme of Shadow Factories. The importance of the supply side of the industry was recognised, with corresponding support of developments in the provision of engines, propellers, undercarriages, light alloys and their products, machine tools and others. The Ministry was now directly represented at all final assembly plants by Resident Technical Officers. A new Directorate for Production was formed, to undertake the preparation and organisation of output programmes, with a statistical section for processing the data required, obtained through greatly-expanded recording arrangements across the industry.

Prior to the declaration of war in 1939 these efforts were augmented and the pace stepped up, and a new Ministry of Aircraft Production was instituted in 1940. The overall aim was to reach the War Potential level of output. This had been outlined and updated over some years previously, to keep in view what would be required to obtain the capacity needed to sustain all air operations needed in a lengthy war. The level was reached and passed by the end of 1942.

After 1943 the capacity of the British aircraft production system was determined largely by the size of the workforce that could be allocated to it. The machines and engines of the earlier years were succeeded by new types in every category, but no substantially new developments were needed in the planning or the production technology involved. The RAF and FAA were further strengthened by the supply of US aircraft under Lend-Lease. As the conflict in Europe entered the land-war phase, it became possible to contemplate ultimate victory in that sector. More attention could then be given to the requirements for increasing action in the Far East, where the very different climate from the European theatre required various processes of 'tropicalisation' to be applied to military equipment of every kind.

In the peak output month of May 1944 the aircraft industry employed 1.8 million persons and produced more than 2,600 machines of all types, after which orders began to be reduced as it became possible to envisage the coming end of the conflict. Ritchie considered the expansion of this industry and its performance to have been 'the single most outstanding accomplishment of the British war economy' (6). Coordinated and detailed planning, both within the industry and at the relevant government Ministries, had been an essential element in that prodigious achievement.

Connolly calculated a figure of 145,029 aircraft for the planned total production of all types by British firms in the Air Ministry and MAP programmes over the complete years 1939 to 1945, with the correct transition dates between them where they overlapped, and minor adjustments counted (70). The actual output over this period was 132,998 aircraft, more than 90% of that planned figure.

10.2 Envoi

The Connolly bequest includes a folder, originally belonging to a colleague Thurstan James, labelled 'Production'. Among its miscellaneous papers is one of unknown origin headed "Halifax" Group Production (71). This Group consisted of the parent firm Handley Page Ltd, with four agency factories and their sub-contractors, devoted to producing the Halifax heavy bomber shown in Figure 8. It is reported that building one of these aircraft involved making, inspecting and assembling 254,000 parts and incorporating two thousand items of embodiment loan equipment. Materials required for this were two-thirds of an acre of light alloy sheet, weighing 7 tons, 3 miles of rolled or drawn sections and 5 miles of extruded sections, that had been cut, formed and variously machined. These components were then progressively assembled in a series of jigs and fixtures specific to the type. Lengths totalling 3 to 4 miles of electric cable and one mile of pipework had been installed, and between 600 and 700 thousand rivets closed during assembly.

At peak output, the Group was producing Halifax bombers at a rate of one per working hour.

Acknowledgements

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At Cardiff University he was Professor of Energy Studies, Head of Department and Dean of the Faculty of Engineering. For work on the evaluation of new energy sources he was awarded the James Watt Gold Medal of the Institution of Civil Engineers. In 1990 he was President of the Institute of Energy and elected Fellow of the Royal Academy of Engineering in 1993.

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