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Open versus closed innovation: development of the wide strip mill for steel in the USA during the 1920's

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A paired comparison is made between rival attempts to develop the first continuous rolling mill for wide strip in the USA during the 1920's. One firm was secretive, the other relied upon collaboration. Development of the wide strip mill is a natural experiment comparing closed and open innovation since two firms were competing for the same target using different institutional arrangements for their R&D.

Wide strip rolling technology was developed by rival teams in the USA during the mid-1920's. The less successful team at Armco, Ashland, Kentucky was closed to outside influences. Breakthroughs came from Columbia Steel at Butler, Pennsylvania which pursued an open pattern of cooperation with equipment suppliers. Columbia Steel's collaboration with machinery suppliers, use of independent advice on bearing technology and willingness to learn from precursors in copper rolling enabled them to build a successful wide strip mill complex, commissioned in 1926. Butler established the dominant design for the next 80 years. The leading equipment supplier at Butler, the United Engineering and Foundry Co., led global sales of the technology for four decades.

It is not clear how far this example of successful open innovation in the US inter-war economy is typical. Historical studies of the management of R&D focus on formal, science based research in large corporate labs rather than engineering development.

"A trip through the plant causes to be raised the question – 'how was it possible to assemble such rolling mill equipment, so drastically different from that of any previous installation and adapted to the rolling of high-finished flat or coiled steel without encountering no difficult operating problems at the outset?' "

Comment on Columbia Steel, Butler written in the vernacular by John D. Knox (1927c, *1400 and 1433*)

1. Introduction

Modern approaches to innovation management stress the importance of distributed innovation (Howells *et al*, 2003), or networks of innovation (Powell *et al*, 1996), captured by the idea of "Open Innovation" (Chesbrough, 2003). Development of the wide strip mill for steel in the USA during the 1920's shows open approaches to innovation are not a new idea. Chesbrough and Crowther (2006) suggest Open Innovation is a useful paradigm for innovation beyond high technology and is appropriate for traditional and mature industries. This paper suggests it is also a long established approach.

This paper reports a paired comparison of rival attempts to develop the first continuous rolling mill for wide strip in the USA during the 1920's. One firm was secretive, while the other relied upon collaboration. Development of the wide strip mill was a natural experiment on the effectiveness of open innovation since two firms were competing for the same target using different institutional arrangements for their R&D. The example also poses a subsidiary question: was open innovation widespread during the early 20th century?

2. What is a continuous wide strip mill and why was it so important ?

The continuous wide strip mill for steel was a revolutionary innovation in 20th century manufacturing which enabled the mass production of cars, cans and consumer durables. In particular, unavailability of wide steel sheets was a key bottleneck for the early US auto industry. "It is the large volume buyer, such as the automobile builder, who has given encouragement to the new pioneering", the trade journal *Iron Age* asserted in its editorial on "The revolution in sheet rolling" (1927(a)).

Poor quality, limited dimensions and restricted supply of steel sheet constrained early car body design, raised costs and inhibited output (Fanning, 1952). Quality and availability of wide steel sheet was a "reverse salient", a point where technology had fallen behind in the broad development of vehicles (Hughes, 1983). Rolling has been used for the plastic deformation of iron and steel since early experiments by Henry Cort from 1780 onwards (Beynon, 1956). Rolling was largely a batch process with individual pieces of steel rolled in one mill stand at a time. Steel needed to be "squeezed" down whilst hot from a cast ingot through repeated steps of rolling on a mill stand and re-heating as soon as the material cooled. The hot material was largely manipulated by hand. Eventually, the thinnest sheets could be rolled cold, although they required subsequent annealing to remove "strain ageing".

Steel sheet rolled on hand mills was not sufficiently wide, uniform or ductile and exhibited poor surface quality. The output of hand mills was individual pieces of thin steel of limited dimensions and varied metallurgical characteristics. Hand mills had to contend with labour shortages – hand rolling was hot, dirty and labour intensive, even by standards of the time.

The key barrier for strip was rolling large volumes of wide, flat steel continuously, rather than as individual sheets. Continuous rolling means hot steel flows through a sequence of stands, without interruption and without any intervening re-heating or manual handling. On a continuous wide strip mill, one piece of steel is rolled through all the finishing stands at the same time. A central difficulty is that steel elongates as it rolled thinner, so successive stands have to roll progressively faster and the speed of stands has to be synchronised to prevent either breaks under tension or accumulation of strip between stands as "cobbles". (Some mills are "semi-continuous" because they are configured with reversing roughing stands to roll down the initial steel slab. But they follow the same principle of unbroken flow from reheat furnace to coiler through a continuous finishing train.)

The ultimate prize was very long, wide coils of hot rolled steel of uniform quality. Coils meant much heavier piece weights bringing economies of scale. Manual handling was eliminated. Coils were also a key logistics innovation since they are fed continuously into subsequent processing stages such as cold rolling and manufacturing steps downstream such as car-body presses or canning lines. So there were system-wide gains realised by the switch to steel sheet in coils.

3. Open versus closed innovation

Continuous rolling of wide steel strip was pursued independently by rival teams at the American Rolling Mill Company (Armco), Ashland, Kentucky and at Columbia Steel, Butler, Pennsylvania.

Armco relied exclusively upon its own organisational resources as America's leading sheet producer. Armco's development of the continuous sheet mill was the outcome of a systematic research and development programme conducted in great secrecy. It proved a false start.

In contrast, the Columbia Steel mill at Butler, Pennsylvania relied heavily on reciprocal cooperation with machinery manufacturers and bearing suppliers for its successful development. As a result of collaboration, a technical community of practice developed around the idea of continuous rolling on four-high mill stands using roller bearings and electric motor speed control. The exchange of know-how seems to have developed on the basis of personal relationships and trust.

In evolutionary terms, these two competing developments represent the generation of variety towards solving a pressing technical problem (Nelson and Winter, 1982). Rolling mill builders and engineering teams in US steel companies soon selected the Columbia Steel approach developed through open innovation. Paired comparisons between success and failure have a long tradition in innovation studies (Freeman, 1973.) Here we are testing a hypothesis, rather than seeking to generalise on the basis of case studies (Eisenhardt, 1989; Yin, 2003). While it is tempting to generalise, a single paired comparison is not sufficient basis for a generalisation that the open approach is superior – though it might well have refuted the hypothesis. Innovation is far more messy and contingent. We judge the Columbia Steel team of Townsend and Naugle were better designers than Tytus and Hook, their rivals at Armco. But Columbia Steel also had more technical support as a result of their open approach. It is difficult to establish how far the radical innovation at Columbia was due to open collaboration and how far it reflected the flair and inventiveness of Townsend and Naugle.

The history of the wide strip mill is unresearched. Early developments of the wide strip mill were shrouded in secrecy, or as it was delicately expressed at the time "the companies owning these mills have been extremely reticent in regard to operating details" (Shover, 1928). Armco did not allow any visitors to their plant until it had been operating for three and a half years (Crout and Vorhis,1967,142-3). Loss of archives relating to the initial development hinders research.

This attitude of secrecy faded as the technology diffused across the US steel industry. Extraordinarily detailed technical publications (Ess, 1941) and a sequence of visit reports attest to growing openness of US strip mill operators and pride in their achievements (Sheet Trade Board, 1938; Hot Mill Team, 1959). Their candour and hospitality accelerated the diffusion of the hot strip mill worldwide, helping US plantmakers export by offering potential overseas customers access to their domestic reference plants.

4. Wittgenstein's father and other precursors

The continuous wide strip mill had precursors, notably at Teplitz in Austria between 1892 and 1907 where Karl Wittgenstein, the philosopher's father was heavily involved in research and development as mill engineer and owner. In the USA, the American Tinplate Company experimented with a continuous wide strip mill between 1902 and 1905 at their Monongahela Works (Ess, 1941, 3-4; Hogan, 1971, 846-7). Designed by C.W.Bray, the mill aimed to roll thin tinplate sheets. The mill was a sequence of eight stands. Tinplate bar was rolled down in the first six stands and then "packed" two pieces thick for rolling in the last two stands. High scrap loss, poor yield of prime material and roll breakage caused the mill to be abandoned. A similar mill was then built by the same company at their Mercer Works in Pennsylvania, commissioned in November 1905, to roll thicker gauges, rolling packs of three sheets in the final three stands. This experiment failed for the same reasons and the mill was dismantled in 1910.

Evidently, the idea of rolling wide sheet on successive stands was a problem to be solved, driven by demand from the rapidly growing American car industry. But the new continuous sheet mills were limited in width to around 20 inches. For example, Morgan Construction Company built a 21 inch multi-stand mill for Sharon Steel Hoop Co. to continuously roll sheet bars and slabs (*Iron Trade Review*, 1920 and 1929).

These narrow mills were a step on the road to continuous rolling, but a long way short of the modern wide strip mill as they did not roll the width required by customers, nor have four high stands for accurate gauge, nor the synchronised motors that are characteristic of continuous wide strip mills.

5. A choice of development routes

Successful development of the continuous wide strip mill in the United States represented a combination of existing technologies. Badlam (1927) argued the wide hot strip mill had two distinct origins. The first line of development was mechanisation of a sequence of mills rolling individual sheets to make a continuous flow-line process. This solution was pursued by Armco at Ashland in Kentucky. Essentially, this was an incremental approach to the problem. Armco linked a sequence of batch processes to make individual sheets of steel.

The second route to continuous strip rolling was to make existing *narrow* continuous strip mills wider. This was the successful solution adopted at Columbia Steel, Butler, Pennsylvania in 1926. Butler pursued a continuous process making coils from the outset. Columbia Steel also developed the associated technology of coil handling at their Elyria works in Ohio, which "served as a proving ground and laboratory for the company's newest installation at Butler, Pa." (Knox, 1927c, 1433).

Making a narrow strip mill wider is not as obvious as it sounds: there are difficulties of steering the wider strip through the mill, deflection across longer mill rolls leading to gauge variation across the strip, handling much heavier piece weights, dissipating the heat generated by friction on the roll necks which bear the load and coping with the high power required to make wider strip.

6. Armco at Ashland – rolling sheets in sequence

Armco pursued the idea of rolling of individual sheets in sequence. Armco adopted tandem rolling of individual hot sheets at its Ashland mill in Kentucky which first rolled plate in December 1923 and sheet in January 1924 (*Iron Age*, 1927c). The mill is reputed to have cost $US10 million (around $US65 million at 2007 prices). The mill was designed and built by Armco amid great secrecy using bought-in components from established machinery suppliers which were delivered to the gate, including mill stands from Mesta Machine Co and a blooming mill from United Engineering and Foundry Co (United). The Ashland site was surrounded by a woven wire fence and guarded by security staff. There is no evidence that equipment suppliers participated in any aspect of the development apart from manufacturing components from drawings supplied by Armco.

Armco's development of the continuous sheet mill was the outcome of a systematic research and development programme led by John Butler Tytus and Charles R. Hook (Crout and Vorhis, 1967). Initial trials used sheet mills left idle during the first world war when Armco turned to forging shells (Knox, 1927d, 1534). At the time, Armco was exporting shell steel to the British government. The specifications called for cropping of the ingots by 25 per cent. These discarded crop ends were readily converted to sheet bars for research purposes. They systematically investigated the behaviour of the roll gap, roll temperature, roll composition and gap setting during hot rolling. Tytus and Hook convinced the board of Armco to sanction a commercial scale pilot plant at Ashland using a team of engineers with no experience of rolling so that prior knowledge would not prejudice their work.

The layout of Armco's Ashland sheet mill was unique. It was a three stage process. Essentially it aligned the separate process stages of hand rolling. Ashland used mainly two high mill stands and an intermediate reheating furnace between the initial "bar plate mill" (roughing train) and the intermediate "rough plate mill". The finishing train, or "sheet mill" was characterised by a reheat furnace ahead of the first two stands and then intermediate furnaces ahead of the three final stands, again a replication of hand rolling practice. The mill rolled individual short pieces of sheet which were generally only in one stand at a time, and worked at relatively slow speeds and low temperatures. The final sheet passed through no less than five intermediate furnaces in addition to the initial slab reheat furnace. In effect, Ashland mechanised traditional hand mill technology by developing the rolling process into flow line production, drawing on earlier developments at Teplitz in Germany and Monongahela and Mercer works in the USA

Armco's contribution was roll-pass design (US Patent 1,602,468). It is easy to steer narrow strip using side guides. This was not possible with wide strip. Armco developed the notion that rolls should vary in cross section to "steer" the strip through the mill finishing train, against the prevailing view that roll surfaces should form a true cylinder (Knox, 1927e, 1596; Fanning, 1952, 196-200). Tytus ground the early rolls in the mill with a slightly concave profile, so that the breakdown strip – or "rough plate" as it was known - had a slight convex crown. The crown was reduced as the strip moved through successive stands until the final stand, where the sheets emerged almost flat.

Even so, Armco hedged their bets: the roughing train at Ashland was not straight. The bar plate mill, as it was known, had skewed roller tables between each stand and the alternate individual stands were slightly offset one from another in a zig-zag fashion (Knox, 1927f, 1658). As a result, the breakdown strip was alternately forced against one side guide or another as it moved successively from stand to stand. So, in many respects, Ashland was a false start – a set of individual mill stands linked by offset roller tables. It was later realised that decreasing concavity of the rolls was not crucial either. Rather the important feature for tracking is symmetry of the rolls around their centre line.

7. Columbia Steel, Butler – the first continuous wide strip mill

Columbia Steel developed the first modern continuous wide strip mill rolling coils at Butler, Pennsylvania in 1926 (Ess, 1941, 4). This was the real breakthrough: with Butler, the first continuous wide strip mill had arrived. Generation I had begun.

Columbia Steel Company at Butler targeted the automotive market with their 36" mill which started up on Thanksgiving Day, 26th November 1926. The mill was developed by Arthur J. "Gene" Townsend and Harry M. Naugle on the basis of earlier trials at Masillon, Ohio. The two met in Canton, Ohio where Harry Naugle was chief engineer of the Berger Manufacturing Company and Gene Townsend was an engineer at their supplier, the Stark Rolling Company. With Kenneth Jenson they formed the National Pressed Steel Company in 1916 to make components for the building industry, but with the ultimate idea of making long wide sheets. They sold their idea to Central Steel, which company acquired 90 per cent of the stock. This financed acquisition of Columbia Steel at Elyria and the later purchase of the works of the Forged Steel Wheel Company of Butler, Pennsylvania (Heald, 1955).

The wide hot strip mill at Butler was originally known as a "stripsheet mill" on account of the long length and width of sheet that it produced. It was later said to have cost $2 million (Blast Furnace, 1958).

The significance of the Butler mill was recognised at the time. *Iron Age* (1927b) enthused "as a means of producing higher finished material in large production, the Columbia development spells a new era in sheet steel manufacture". The *Iron Trade Review* used similar superlatives, "Never, so far as can be learned, has an installation adapted to the rolling of steel been completed which has had so many new features incorporated in its design. It is a milestone in the rolling industry" (Knox, 1927a, 1272). In many respects, Butler overshadowed the earlier Armco sheet mill at Ashland which did not open its doors to journalists until a couple of weeks later.

The Butler mill combined a number of novel features crucial to hot strip mill development, including straight through rolling from roughing train to finishing train without reheating; four high finishing stands; a coiler and adjustable speed individual DC drives. The mill had a semi-continuous layout, with a reversing two-high universal roughing stand supplied by two continuous reheat furnaces. There was a closely spaced finishing train built by United. composed of four, four-high stands with loopers to control strip tension. The back-up rolls were equipped with roller bearings. The mill rolled at high speeds and high temperatures with the strip in all four finishing stands at the same time. There was one 2½ ton up-coiler. The wide hot strip mill had arrived.

8. Butler – collaboration with suppliers

Successful development of the wide hot strip mill at Columbia Steel, Butler was helped by collaboration with their plant supplier: United Engineering and Foundry Co. of Pittsburgh. United had begun to develop four high stands. These had two crucial advantages when rolling wider strip. Firstly, the back-up roll acts as a reinforcement to prevent deflection of the work rolls so that strip can be rolled to a near uniform thickness across its full width. Secondly, back-up rolls transmit rolling forces from the work rolls through to the mill stands. This meant the stresses could be borne by roller bearings on the much larger necks of the back-up rolls. Placing the stresses on back up roll bearings solved the problem of transmission of extremely high loads in a confined space (Buhlman, 1927). Use of roller bearings solved the problem of neck friction and consequent heavy power use and bearing wear associated with rolling wider material on a two high mill. Less wear meant greater accuracy in rolling.

The equipment supplier, United, had recent experience at Rome Brass & Copper Company, Rome, N.Y. with the use of roller bearings on a four high mill for copper sheet (Biggert, 1927, 3-4). The Rome mill was strongly supported by F.C. Biggert, the President, General Manager and former Chief Engineer of United, and by Lane Johnson, an MIT educated engineer, former Armco employee and Chief Engineer of United from 1922 (United Effort, 1926, 7, 10). This wide four-high copper mill was developed by Colonel R.C. Jenkins in 1925 in the face of internal opposition at Rome. It has been said Colonel Jenkins contribution to rolling technology should "rank high among those who helped build American industrial supremacy" (Pfeiffer, 1951, 12). Rome was the first modern, four high mill with anti-friction bearings (Badlam, 1933, 343-4).

United had earlier developed a 204 inch wide four high plate mill at Lukens, completed in 1916 for quite different reasons – to avoid having to cast huge work rolls. A surprise side effect was that the four high configuration produced more uniform gauge. United were keen to help Columbia experiment with rolling wide steel strip on four-high mills as they already had an enquiry from Weirton for an even more ambitious wide strip mill, also inspired by the Rome Brass and Copper Company mill development (Pfeiffer, 1951, p.14.) The crucial roller bearings for all these early mills came from William Messinger of Philadelphia (then known as the Hydraulic Tool Company). Messinger had designed roller bearings running in a bronze cage which were ideal for carrying heavy loads in rock crushing machinery and paper mills. "The question of roller bearing design was discussed with Mr W. Messinger of Philadelphia, one of the outstanding authorities in this field and having determined sizes which, upon rather meager data, appeared to meet the requirements, a mill was built. It has proven satisfactory." (Biggert, 1927a).

Messinger's solution was to design a separate radial and thrust bearings for the Rome Mill (figure 4). The relationship with United prospered and Messinger went on to supply the radial and thrust bearings for the wide strip mills for steel at Butler and Weirton (Link, 1929) and collaborate with United on experimental designs.

The 4-high mill with suitable bearings in heavy cast housings made the stands sufficiently rigid to allow accurate rolling of wider material to lighter gauges within acceptable limits.

The Butler wide strip mill of Columbia Steel combined a number of radical innovations that remain widespread 80 years later. A key technical and logistic innovation was the manufacture of continuous coils in place of individual sheets. Butler was remarkable in terms of novelty as it also included a continuous pickle line for cleaning the hot strip, a four stand tandem cold rolling mill brought into operation in December 1926, built by E.W. Bliss and two temper mills (Knox, 1927b,c). All the stands on the cold mills were also of four high configuration with roller bearings on the work rolls and back-ups which suggests United shared their ideas with their rival Bliss, since the firm's machinery catalogue for 1926 shows no four-high mills at all (Bliss, 1926.)

Columbia Steel installed both a continuous pickler and a continuous annealing line for strip at Butler. Each coil was joined to the next automatically by spot welding on a carriage that moved with the strip. The strip was held in place by magnetic clamps while the welding took place. These radical innovations, and many other handling devices were pioneered at their Elyria works in Ohio, which "served as a proving ground and laboratory for the company's newest installation at Butler, Pa." (Knox 1927a, 1433). Columbia Steel had to develop coil handling equipment as hitherto all coils had been narrow, and therefore light enough to be man-handled (Knox 1927a, 1400). The Butler mill made coils up to 2½ tons.

As with many innovations, the key was not one individual development, but a combination of technologies built into a single plant. The principle of back-up rolls, for example, had been around since the three high Lauth plate mill of 1864 (Hoare and Hedges, 1945, 37). Indeed, Ashland used three high stands on its finishing train – probably because they were available second-hand. The distinctive features of Generation I wide strip mills, according to Ess (1941), were the application of 4-high mills and the Ward-Leonard control system for the electric motors.

Variable speed drives are crucial to rolling steel strip. Before this, mill stands were driven by belts or gears (Badlam, 1933, 339). The speed ratio between successive stands was fixed. While this was suitable for rolling simple products, it does not work for strip, as Teplitz showed. The development of individual, adjustable speed DC motors on each stand allowed rolling speeds to be adjusted to suit any gauge. The well-established Ward-Leonard power control system for electric drives at Butler allowed successive stands to be synchronised, making continuous rolling possible (Burr, 1927, 298), a technical problem that challenged paper making machinery too (Goldfarb, 2005; Menzies, 1926).

Electrical progress was crucial for successful development of the hot and strip mill. The technical journal *Iron and Steel Engineer* was founded in 1924 and early issues were largely devoted to electrical engineering. David (1990), points out that the transformation of American industry by electric power technology was long delayed: "factory electrification did not reach full fruition in its technical development nor have an impact on productivity growth in manufacturing before the early 1920's . . .This was four decades after the first central power station opened for business." Rolling mills were a key part of this electrification process in the 1920's. In terms of innovation theory, the wide strip mill was a "complex" innovation in so far as it drew upon knowledge of more than one fundamental technology – both electrical and mechanical knowledge was required to make it a success. In effect, the wide strip mill was located at the junction of two technologies.

The use of coils converted down-stream finishing operations from a batch process to a continuous flow basis. Continuous pickling, cold rolling and annealing became viable. Subsequently continuous tinplate lines, zinc coating and organic galvanising lines emerged. Canning lines and car industry process lines began to use coils in place of individual sheets.

Comparing the cost of the two experiments, Columbia Steel's mill cost one fifth of the price of the Ashland project. It used a second hand building and re-used old reheat furnaces. The mill at Columbia Steel was also a more compact, less elaborate and cheaper design.

It is simplistic to tell a narrative of unbridled success on the part of Columbia Steel. There were doubtless problems. As Scranton cautions (2008, 207) "real engineering at the edge is a gritty process laden with fixes, errors, cursing, and painfully-incremental steps towards something that works, much less works reliably and safely. There's no romance in that, so a more marketable story has long been routinely fashioned".

9. Armco's competitive response

Armco's competitive response to Butler's superior development was simple: Armco rapidly took over the Columbia Steel Company and its patent portfolio in July 1927. Armco paid a price approaching $20 million (Butler Eagle, 1927). Columbia was largely owned by Mellon interests and they secured a shareholding in Armco.

The official reason for the takeover was to avoid patent litigation (*Iron Trade Review*, 1927). But, of course, the takeover gave Armco complete and lucrative control of much continuous wide hot strip rolling technology. Or, as Armco stated: "A very substantial patent structure has been created covering the practical, technical and mechanical problems involved in the entire development at Ashland, Kentucky, and Butler, Pa., Works. This entire conception represents a mechanical and economic development of first magnitude which will undoubtedly have a marked influence on the whole sheet metal industry of the future." (Armco, 1928a, 6).

All of Townsend and Naugle's patents were assigned to Armco when they were finally granted, notably the key hot rolling patent 1,736,324 on "Strip-Sheet Manufacture" filed May 24th 1927 before the takeover of Columbia Steel. The combination of Armco's patent on roll shape and Townsend and Naugle's patents on plant layout effectively sewed up hot strip mill design. Armco also received the Townsend and Naugle patent on cold rolling 1,781,123 - first filed in September 23 1924 but not granted until 1930 - developing the idea of continuous cold rolling of strip under tension. As a result of the takeover, Armco sold worldwide licences for their hot strip mill technology and charged royalties on all strip rolled on continuous wide strip mills.

Ironically, it can be argued that Armco embraced open innovation when they bought Columbia, purchasing the technology they needed for strip rolling through buying an entrepreneurial competitor and their intellectual property and bundling it together with their own know-how on roll-pass design.

10. Diffusion of the innovation

No less than 28 wide strip mills were built in the USA between 1924 and 1939, then equivalent to 16 million metric tonnes of capacity (Ess, 1941, 5). United implemented the lessons of Butler at Weirton Steel, where they had a shareholding. Both Ashland and Butler were made wider and rebuilt in the light of experience. Armco's second mill at Middletown, Ohio was modified with four high stands from United (Longenecker, 1936). United went on to sell the equivalent of 57 wide continuous hot strip mills for steel during its lifetime as an independent, US owned builder. This compares with 36 hot strip mills sold by its nearest rival, Mesta.

A standard or "dominant" design of wide strip mill soon emerged with the construction of the 76" mill at Inland Steel by the Mesta Machine Company, commissioned in 1932 (Davis, 1934; Badlam,1939, 34). This fully continuous mill had three pusher reheating furnaces, a scalebreaker stand, four roughing stands and six finishing stands. Most of these subsequent hot strip mills were built with fully continuous roughing trains as well as continuous finishing trains to solve the problem of heat loss, though the Butler design of a semi-continuous mill re-emerged post-war and became the basis for Generation IV designs from the 1980's (Aylen, 2001).

Not all new mills initially rolled coils. The continuous 42" mill at Gary for Carnegie-Illinois Steel Corporation commissioned in 1927 followed Ashland and rolled sheets in long lengths which were handled at the end of the mill via a huge, 180 ft diameter locomotive size turntable (Hoare and Hedges, 1945, figure 18; Ess, 1941, layout 5). The mill was subsequently retro-fitted with up-coilers (Ess, 1941, table 21, mill 5). Traditional mills continued to be built too: United was supplier of 24 electrically driven handmills for Youngstown Sheet and Tube Company, Indiana Harbor Works which were obsolete once installed (Hogan, 1971, 857-8).

The technology of continuous wide strip rolling diffused extraordinarily rapidly over the next decade encouraged by demand for autobody sheet from US car makers. Apart from the 28 wide strip mills built in the USA, six mills were also built in the USSR, Germany, the UK and Japan before the second world war. Five were direct exports from American plant suppliers while the German mill slavishly copied US design. Marshall Aid brought American strip mill technology to Europe again after the second world war, and American management methods too (Ranieri, 1998, 2000).

The savings were huge: Fanning (1952, 203) reports that "a careful computation based on present-day labor and material costs, applied to old hand mill yields and processing operations shows that 20 gage cold rolled would be selling today at $275 a net ton instead of the present price of $104 a net ton for the new and very much superior product".

11. Why open innovation ? Secrecy versus collaboration?

Why did Armco prefer secrecy and Columbia Steel chose collaboration ? There were mutual gains from collaboration: Columbia Steel wanted access to new mill stand technology while United wanted to develop a new product for a market with huge potential and needed access to an operating mill to develop their know-how.

Columbia had already worked with United Engineering and Foundry Company, Pittsburgh on their narrow continuous cold rolling mill at Elyria, Ohio, commissioned in Feb. 16, 1923. United had developed the four high principle at Lukens Steel and was working at Rome Brass. United's response to Columbia's proposal to develop a continuous wide strip mill was:

> "Here was a chance to try out the 4-high principle in a big way, but only imperfect data on which to base designs were available. We decided to make a clean breast of the matter and see if Columbia would go along with us in a large scale experiment. The allurements were great and we convinced them that the experiment was worth making." (Biggert, 1927b, 1237)

United not only built the hot strip mill, they also added monitoring devices for research to measure pressure and friction to improve future designs. There must have been a high degree of cooperation: notice that United's rival Bliss also used the four high concept and roller bearings on the continuous wide cold mill at Butler, though they turned to a different bearing supplier.

Columbia was open innovation in so far as the key features of four high stands and roller bearings would not have been pursued without mutual cooperation between steelmaker, plant supplier and bearings manufacturer. All parties saw clear gains from pooling their knowledge. Personalities played a key role, in terms of informal cooperation, transfer of tacit know-how and individual inventiveness. As the patents attest, the numerous innovations on layout, manufacture of coils, coil handling, pickling, annealing and continuous cold rolling were attributable to Townsend and Naugle. Close personal cooperation brought other rewards: Harry Naugle was elected a director of United in 1931.

In contrast, Armco had a long tradition in hand rolling steel sheet and building its own rolling mills. It had acquired a new works for expansion at Ashland, had its own drawing offices and a team of engineers (Crout and Vorhis, 1967). Armco also had a track record of successful R&D in manufacture of pure iron and an R&D Laboratory at Middletown, Ohio (Armco, 1928b). Their know-how on conventional hand rolling was in demand: Armco managed part of the sheet plant at Shotton in North Wales, helping John Summers & Sons supply the car industry, in return for royalties (Summers, 1940; Aylen, 2008). They pursued an in-house R&D programme on deep drawing sheet suitable for autobodies (Griffis *et al*. 1933).

Closed innovation meant Armco used traditional brass roll-neck bearings, despite the friction, heat and the wear (Ess, 1941, part II, 2). Wear on conventional bearings is a particular problem when trying to rolling thin gauges accurately. Friction consumes power (Weckstein, 1935). Timken estimated at the time roller bearings halved energy consumption (Pruitt, 1998) on steel rolling mills. Moreover, brass bearings need intermittent lubrication so they cannot roll continuously under load. Conversation with United would have revealed their plans for using roller bearings in four high stands.

12. Open innovation: how common in history ?

The Armco/Columbia race raises the question: how typical was their experience? It is not clear if Columbia Steel was an isolated instance of open innovation as there are few historical studies of R&D management in the USA and even fewer in the UK.

A survey by Edgerton and Horrocks (1994) shows an important feature of inter-war R&D was that many of the largest R&D performers in the UK were either foreign owned or participants in international or national cartels, patents pools and scientific agreements. The example of Metropolitan-Vickers in Manchester suggests there was considerable cooperation between industry and academia, largely as a result of the first world war (Cooper, 2007). In chemicals, Du Pont and ICI had a patents and processes agreement that led to extensive sharing of know-how between 1929 and 1948.

There is a problem of sample selection bias: historians study what is amenable to study and the archives of large R&D labs. are tempting targets. Studies also focus on aspects of corporate research that are close to science (Israel, 1992, 185). It is not clear how far the documented experience of Du Pont, GE, Bell, Kodak or Alcoa are typical of all R&D conducted in the USA during the 20th century (Graham and Pruitt, 1990; Hounshell and Smith, 1988; Reich, 1985; Dennis, 1987; Graham, 1985). The case of Alcoa shows a high degree of research collaboration during the second war, though this tailed off when competitors were strengthened by the sale of wartime plants. Alcoa collaborated with United Engineering and Foundry Company, reflecting United's considerable pre-war experience in the development of large aluminium rolling mills for Soviet industrialisation. Prior to this, United boasted in 1938 about their mills at Zaporozhe that "not even the Aluminum Company of America has machinery as modern" (Sutton, 1971, 58-60).

The history of formal R&D has been neglected, but there are even fewer studies of the important role of engineering departments. In the context of early electrical engineering Hughes (1983, 161) observes "There are countless examples of critical problems being solved by manufacturers' engineers". Fox and Guagnini (1999) point to Ferranti's struggle to commission the Deptford Power Station. Collaboration between producers and their equipment suppliers has a long history, dating back at least to Henry Maudslay's collaboration with Marc Brunel over the pioneering Portsmouth block-making factory started up in 1803 (Gilbert, 1965; Cooper, 1984).

No doubt, networks were as crucial to successful innovation in inter-war America as they are now – we do not have the evidence. Rosenberg (1982) emphasises machinery and equipment suppliers play a crucial role in 'learning by using'. Feedback from operational experience improves the design of capital equipment. In a case analogous to steel, Freeman's (1968) study of chemical plant shows how process plant contractors - a group of specialised design, development and construction companies – came to dominate the transfer of continuous process technology, even though oil and chemical companies remained the major source of technical innovations. Licence flows and know-how agreements lubricated the complex exchange of technologies embodied in a major chemical plant (also Rooij, 2005).

A distinction can be drawn between "open" information flow between equipment suppliers and users discussed here and collaboration between companies who might otherwise compete directly in the product market. In the UK, Sanderson (1978) shows some 40 Sheffield steel companies joined a semi-secret body called "Sheffield Steel Makers Ltd" to share technical know-how and advice during the early 20th century, followed by a national cooperative "Iron and Steel Industrial Research Council" formed in 1929 (Carr and Taplin, 1962, ch.46), in turn succeeded by the post-war British Iron and Steel Research Association (Spenceley and Scholes, 2001). A rare study by Divall (2006) finds the biggest inter-war railway company in the UK relied upon a network of external experts as well as its own in-house engineers for its industrial research.

The full history of R&D management remains to be written. Studies of past development projects offer potential lessons for current technology management, with the added advantage the outcome of past research is known. Wider impacts of the R&D process upon users of new technology, suppliers and rivals can be assessed with hindsight. Study of past research highlights the changing history of formal R&D management (Boersma, 2007). By its nature, tradition is overlooked in a forward looking discipline.

13. Conclusion

This paper reports a paired comparison of rival attempts to develop the first continuous rolling mill for wide steel strip in the USA during the 1920's. Development of the wide strip mill is a natural experiment comparing closed and open innovation: two firms were competing for the same target using different institutional arrangements for their R&D. One firm was closed to outside influences, the other relied upon a network of support.

The less successful team at Armco, Ashland, Kentucky was highly secretive. Breakthroughs came from Columbia Steel at Butler, Pennsylvania which pursued an open pattern of cooperation with equipment suppliers. Columbia Steel's collaboration with machinery suppliers, use of independent advice on bearing technology and willingness to learn from precursors in copper rolling enabled them to build a successful wide strip mill complex, commissioned in 1926. The Butler continuous wide strip mill established the dominant design for rolling steel strip for the next 80 years.

Development of the wide strip mill offers a sharp contrast between technical success and failure, but inference about open innovation as the best way to manage R&D should be more cautious. Arguably, the winning team of Townsend and Naugle at Butler were also better inventors than Tytus and Hook at Ashland. While the race to develop wide strip rolling of steel refutes a null hypothesis of no difference between open and closed innovation, there is sample selection bias. Development of the wide strip mill is one undocumented case among many in an era of innovation. It is not clear how far this example of successful open innovation in the US inter-war economy can be generalised, although it is not unique as other innovators have collaborated with equipment and component suppliers. Histories of R&D management focus on formal, science based research in large corporate laboratories rather than the process of engineering development. The history of R&D management remains an under-researched area.

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15. Figures

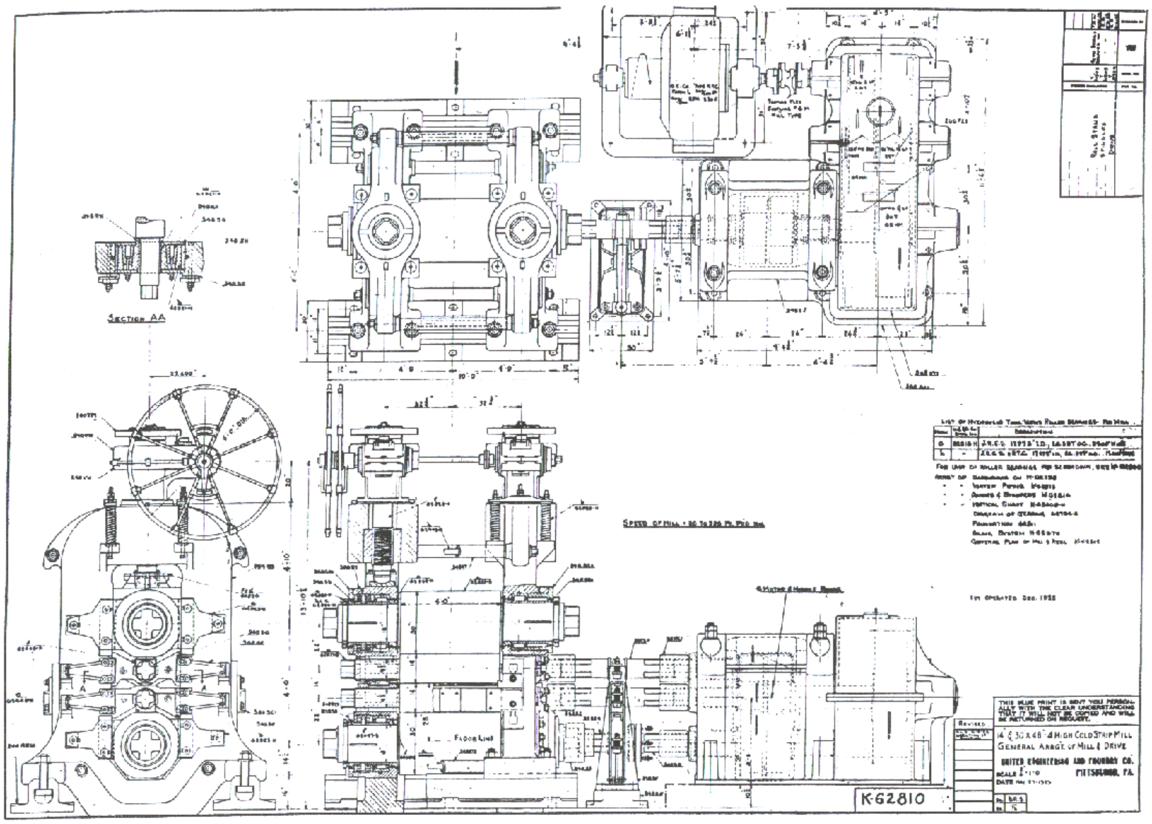

Figure 1. The original four high wide strip mill stand for Rome Brass designed by United Engineering and Foundry Company of Pittsburgh with roller bearings from William Messinger's Hydraulic Tool Company.

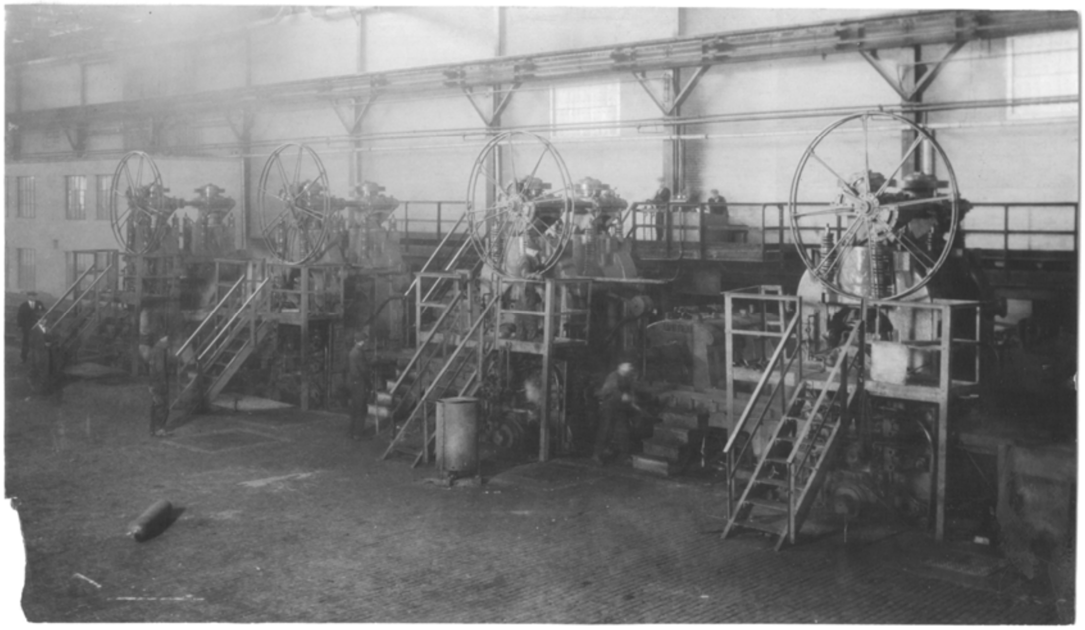

Figure 2. The continuous wide hot strip mill finishing train of Columbia Steel, Butler, Pennsylvania with United Engineering and Foundry Company four high stands and Messinger roller bearings – Townsend and Naugle appear to be standing on the extreme left of the picture (courtesy of the Hagley Museum and Library, Delaware)

Figure 3. United Engineering and Foundry Company earlier collaborated with Columbia Steel to develop continuous cold rolling of strip at Elyria, Ohio from 1923. Although only a set of narrow two high stands, it helped Columbia Steel pioneer continuous cold rolling and coil handling. The loose coils in the foreground are narrow hot rolled strip awaiting cold rolling. (courtesy of the Hagley Museum and Library, Delaware)

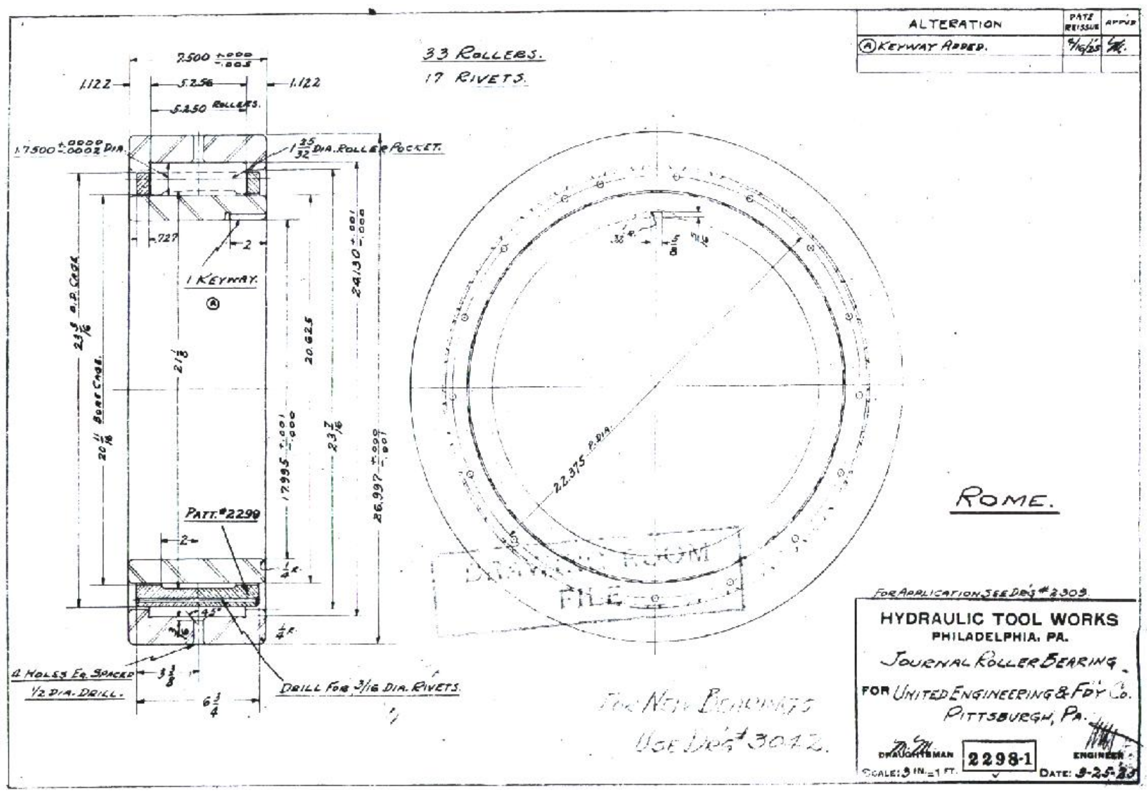

Figure 4. United Engineering and Foundry Company approached William Messinger of the Hydraulic Tool Company in Philadelphia for advice on roller bearings for the back-up rolls to the four high mill at Rome Brass. This is drawing 2298-1 of a Journal Roller Bearing, marked "ROME", one of a number of drawings of journal and thrust bearings for the Rome Brass project dated 3-25-25. The bearings are composed of an outer forged steel ring and a fixed bronze bearing race holding steel rollers in position. (courtesy of Messinger Bearings, Drummond Road, Philadelphia)