

Complementarity constraints and induced innovation: some evidence from the First IT Regime

Citation for published version (APA):

Reinstaller, A., & Hoelzl, W. (2003). *Complementarity constraints and induced innovation: some evidence from the First IT Regime*. MERIT, Maastricht Economic Research Institute on Innovation and Technology. MERIT-Infonomics Research Memorandum Series No. 027 <https://doi.org/10.26481/umamer.2003027>

Document status and date:

Published: 01/01/2003

DOI:

[10.26481/umamer.2003027](https://doi.org/10.26481/umamer.2003027)

Document Version:

Publisher's PDF, also known as Version of record

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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- The final published version features the final layout of the paper including the volume, issue and page numbers.

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MERIT-Infonomics Research Memorandum series

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2003-027



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Complementarity constraints and induced innovation: some evidence from the First IT Regime

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Abstract

Technological search is often depicted to be random. This paper takes a different view and analyses how innovative recombinant search is triggered, how it is done and what initial conditions influence the final design of technological artefacts. We argue that complementarities (non-separabilities) play an important role as focusing devices guiding the search for new combinations. Our analysis takes the perspective of technology adopters and not that of inventors or innovators of new products. We illustrate the process of decomposition and re-composition under the presence of binding complementarity constraints with a historical case study on the establishment of the First IT Regime at the turn of the 19th century.

Keywords

Technological regimes, systemic innovation, adoption of technologies, complexity, information technology 1870-1930

JEL

D24, N60, O31, O33, L69

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Acknowledgements:

We thank Koen Frenken for helpful comments.

Forthcoming in: Foster J. and Hözl W. (eds. 2004) *Applied Evolutionary Economics and Complex Systems*, Cheltenham: Edward Elgar

1. Introduction

Schumpeter (1939) distinguished three stages in the process of technical change: (i) invention, i.e. the act of creation of a new technology, (ii) innovation, its commercial introduction, and (iii) diffusion, its gradual adoption. Evolutionary economists recognised the importance of Schumpeter's trichotomy, but in the past their work has mostly focused on the last two stages of the process. The inducements and focussing devices leading entrepreneurs to produce new combinations are not analysed in an appropriate way. Technological search is often depicted to be random. Neoclassical work on technical change has long studied John Hicks' induced innovation hypothesis in the framework of aggregate production functions. The key insight is that "a change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind directed to economizing the use of a factor which has become relatively expensive" (see Hicks (1932), pp. 124 - 125). This literature studies the inducement mechanism relying on the principle that a rise in real wages will trigger labor-saving innovation. The problems arising from this type of work is that the aggregate production function framework seems not to be appropriate as technological change is an inherently microeconomic phenomenon. Secondly, Neo-classical production functions of the Cobb-Douglas, CES or translog type are strongly separable. Separability amounts to the claim that the marginal rate of substitution of any pair of inputs is unaffected from changes in the level of another input.¹ Inputs or groups of inputs cannot be complementary. As the innovation process is not only a micro-economic phenomenon but also determined by the systemic character of firms and the technology they use, this assumption is quite strong.

The aim of this paper is to analyse how recombinant search is triggered, how it is done and how initial conditions influence the final design of the technological artefacts resulting from this process. We argue that complementarities (non-separabilities) play an important role as focusing devices guiding the search for new combinations. Our analysis takes the perspective of technology adopters and not that of inventors or innovators of new products (section 2). We illustrate the process of decomposition and re-composition under the presence of binding complementarity constraints with a historical case study on the establishment of the First IT Regime at the turn of the 19th century (section3), and conclude this paper with a discussion of our results (section 4).

¹ For a discussion see Fuss, et al. (1978), p. 244 ff.

2. Complementarity constraints and the direction of technical change: the transition towards a new technological paradigm

The viability of a system depends on how well its different elements fit together. Complementarity refers to the relationship between these elements, that is how they mutually influence their performance. An example for a technical system, exhibiting complementarities is the modular system of the personal computer: The choice of best components (processor, motherboard, graphic adapter, software, etc.) does not necessarily imply that this computer works better than another one, which consists of syntonic but 'inferior' components. The PC consisting of 'best components' may even not work, for example if the 'best' processor cannot be put on the 'best' motherboard. Firms can also be seen as entities that channel inputs into a complex organisational structure, characterised by the technology in use. Firms bundle activities into a productive entity by interconnecting them. Some of the links in the resulting network can be very strong, while others may be weaker. These linkages and their strength can result from strict technical (or static) complementarities between elements in this web but also from tacit or explicit dynamic complementarities, that capture learning spillovers. They exist between inputs of an activity, between activities of a firm and between firms.

Complementarities imply that elements in a system are not separable. Taking the personal computer metaphor as example, complementarities imply that a PC may work worse or better with one or another hard disk controller, but it will not function without one. The PC as a system is thus non-separable from this component. The implications of non-separabilities can be illustrated with Stuart Kauffman's NK model (Kauffman (1993)), which provides an easy way of thinking about complementarity interrelationships in systems. This model has been used in recent times by several contributors to evolutionary economics to study the way economic agents explore a fitness landscape of technologies or organisational set-ups in the presence of complex feedback mechanisms (see e.g. Frenken et al. (1999)). The NK model simulates the evolution of complex systems in which the elements function interdependently. A system is described by a set of N elements each of which can take on A_i possible values. The number of all possible strings among system elements is called the possibility space S of a system. Its size is given by the cartesian product of the possible values: $S = A_1 \times A_2 \times \dots \times A_N$. If a system consists of three binary elements ($N = 3$; $A_i = 2$), the size of S is equal to $S = A_i^N = 2^3 = 8$. This could be interpreted as a production technology with three inputs or activities, which may take two states: 0 if a productivity enhancing innovation for this input is absent or 1 when it is present. S would be the space of technological designs. The fitness values of the 8 possible designs are taken to represent a productivity measure. Each input makes a contribution to the total productivity of a design. K denotes how interdependent the inputs are. Two extreme cases can be contrasted: if $K = 0$, each input's productivity contribution

is independent of all others. In this case one global optimum exists and it depicts the case of a perfectly separable Neo-classical production function. At the other extreme we have maximum complexity ($K = N - 1$), where each inputs productivity contribution depends on all other elements. The number of possible optima in this landscape increases with N and K . The number of optima is a measure for the complexity of a system. Very complex ones have many possible 'good', that is locally optimal, designs. The interrelations need not be symmetric. Matrices a) and b) in figure 1 show this in the generalised NK model of Altenberg (see Altenberg (1994), Altenberg (1997)). Matrix a) is symmetric ($N=3$ $K=1$), as every input is linked to another. Matrix b) instead shows the asymmetric case, where only input I_1 influences the two others. The C_x indicate technical (Lancasterian) characteristics each of the inputs. The matrices in figure 1 map technology or inputs into technical characteristics. In terms of the approach of Saviotti and Metcalfe (1984) the inputs could be defined as process technology and the technical characteristics these produce as product technology. It shows that a characteristic C_x may be influenced by several activities, while one activity in turn may influence several of these output characteristics. So I_1 produces output characteristic C_1 and influences the output characteristics C_2 and C_3 produced by activities I_2 and I_3 respectively, while output characteristic C_1 results from the joint action of processes I_1 and I_3 .

In a recent paper Frenken (2001) argued that activities mediating the interactions of many others constitute the 'core' of an evolving technological paradigm. The more complex the process technology is, the higher is the likelihood that a change in one component may conflict with the overall performance. This implies that elements in the core are more likely to be changed only rarely so that the performance improvements in a technological paradigm take place mostly by adding or changing inputs that are peripheral, such as inputs I_2 and I_3 in matrices c) and d) in figure 2. Even though the system may be more frail with regard to changes in its core, which also restricts the set of profitable moves in the possibility space, it also increases the probability of evolution towards a stable and profitable set-up and reduces technological uncertainty (see Caminati (1999)). The core represents a design of a process technology that works and that can be further explored.

	I_1	I_2	I_3
C_1	X		X
C_2	X	X	
C_3		X	X

a)

	I_1	I_2	I_3
C_1	X		
C_2	X	X	
C_3	X		X

b)

Figure 1: a) Symmetric linkages $N=3$ $K=1$. b) Asymmetric version.

In a stable economic environment entrepreneurs have an incentive to keep the core elements of their operating technique as they are. If economic conditions change, through events that punctuate

the equilibrium, for example shifts in customer preferences or sudden and persistent rises in the prices of some inputs, the strong complementarities in the core may turn into binding constraints. The complementary relations may cause imbalances between related technologies. While under stable conditions complementarities enable the search for new variations of working designs under radical change, they hinder the exploration of new designs. There is an incentive for firms to break up the constraints of complementarities between the different elements of the core and increase its degrees of freedom. Complementarities become powerful focusing devices for technical change. The outcome of the ensuing process of technological search is likely to give rise to radically new solutions, which may entail a complete break-up and reconfiguration of the core.

Schumpeter (1947) described the entrepreneur as the architect of new combinations. Recombining is the ability to recognise linkages between technologies that lead to new products, new output characteristics or increased productivity. If the technological system is complex it is a non-trivial matter to infer the properties of the whole. It is unlikely that innovators know about the existence and entity of all linkages. Simon (1996) suggested with the *Tempus and Hora* parable that the best strategy to manage complex problems is to reduce the number of distinct elements in the system by grouping them into subsystems through the suppression of less important relations. The transformation of a complex system into a nearly decomposable one is a process of problem decomposition. The linkages between the single parts and the laws of interactions have to be understood and codified before any process of recombination can start. Von Hippel (1990) emphasised the importance of task-partitioning as an important feature of the innovation process. Cowan and Foray (1997) suggested problem decomposition to be a slow and stepwise process of codification, which involves the modelling of knowledge. The recursive application of the subdivision of tasks leads to an ever better understanding of the relationship between different skills, routines and heuristics, reducing their tacitness or leading to a better understanding of the source that generates strict complementarities. Decomposition is thus a slow process of identification and selection of links to modify the economic performance of artefacts and activities. In this process past experiences are important starting points. For example, as we will see in the case study that follows, the experience American engineers gained in redesigning products to use standardised and interchangeable parts was prior procedural knowledge in the efforts to reorganise the administration.

Task partitioning and codification are the first steps towards the emergence of a new technical and/or organisational architecture. The process of re-composition is a co-evolutionary process in which managers searching for new process technologies and suppliers of new technological artefacts interact. In this interaction technical change takes place at the level of activities and the

level of artefacts. The role of technology suppliers is to provide a variety of new technological artefacts, which the adopters will explore. The new machines embody some of the knowledge codified during the process of decomposition. This can happen when the division of labour has progressed so far that skills and tacit knowledge related to some original inputs are reduced to chunks of structured information. Then a complete codification and embodiment into specific control mechanisms of machines become feasible. Technological closure on the artefacts and dominant designs emerge as soon as a well-defined domain of application is established, that is the process of re-composition settles to some defined architecture of the process technology. There is a considerable amount of literature starting with Tushman and Anderson (1986), that has studied this process in detail. Several mechanisms are at work in the process of re-composition. Adapting the work of Wagner and Altenberg (1996) to the economic context, we identify two main influences guiding the act of searching for new process technology designs on the part of entrepreneurs: first, they will try to isolate and substitute those activities which in the act of decomposition have been identified as causes for imbalances in the process technology. Second, they will try to avoid negative influences of the new technology on other parts of their core activities, in order not to lose out to their competitors, i.e. they will try to stabilise the function of all other parts of the process technology. The particular skill of the designer of the new process technology lies in selecting linkages that modify the product technology in such a way as to eliminate the causes that have triggered the process of technological search but keep it consistent with the needs of the markets in which the firm operates. Wagner and Altenberg (1996) suggest two mechanisms for regrouping linkages. The first is called *parcellation* and it consists of the suppression of interconnections of lower importance between activities influencing the same group of characteristics of the product technology. The second is *integration* where linkages are selectively established between previously unrelated parts - new and old - of the process technology. Both favour the development of a more modular design of the process technology.

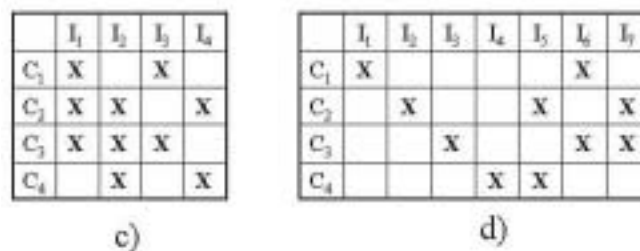


Figure 2: c) Asymmetric linkages in a generalised NK model with two core inputs I_1 and I_2 . d) Decomposed version with perfectly modular core inputs (I_1 - I_2) and new co-ordination or interface inputs (I_3 - I_7).

If these mechanisms are also in place also in the process of technological search and adoption, then one should first expect a differentiation of existing capital goods and work profiles to the more restricted scope of new activity groups and the integration of new capital goods and work profiles. This entails a process of capital deepening, meaning that the quality of the capital stock is improved

in terms of its effects on labour productivity. Second, the re-grouping of activities should make process technology more modular. A more modular and less integrated structure at lower levels of the process technology requires integration at a higher level. This implies that the hierarchical structure should deepen. Theoretical results from the generalised NK model support this view because they show that the likelihood of successful improvements increases in modular technology-characteristic maps, as they are less likely to be offset by negative feedbacks (see Altenberg (1994)). Modularity increases the evolvability of the system as illustrated in figure 2: Matrix c) shows a system with four inputs producing output characteristics C_1 to C_4 . Inputs I_1 and I_2 are highly interrelated with each other and the two other inputs. They constitute the two cores in the organization and technology of the firm. If I_1 for example changes, I_2 and I_3 are affected through feedbacks. Matrix d) instead shows a perfectly modular production architecture in which inputs I_1 to I_4 are not related to each other, and inputs I_5 to I_7 are interfaces relating them. Improvements in any of the "productive" inputs I_1 to I_4 do not influence any other, and the interfaces mediate only between two of the first four inputs. Thus the process technologies dependence on one or more activities is reduced, that is the number of inputs with high K is reduced. This comes at the expense of more, yet highly specialised, inputs. Once such a design of the process technology has been achieved, the system can gradually be improved without incurring the risk of systemic collapse. It opens the way for a series of continuous improvements in the single inputs of the new set-up.

3. Complementarity constraints in the transformation of office work, 1880-1930

The emergence of large administrative structures in manufacturing in the United States at the turn of the 19th century was the result of a process of adaption of firms to gradual and sustained changes in their economic environment. An information-processing administrative body within the firm became a necessity, as economies could be achieved through better co-ordination. The necessary change in entrepreneurial strategy led to a new structure of firms (Chandler (1962), Chandler (1977)). Its operational implementation is discussed in Litterer (1963), Yates (1989), Levenstein (1998) and Hölzl and Reinstaller (2000).² We offer an interpretation of this process in accordance with the framework put forward in the preceding section.

² For references and a more detailed account of the historical development see Hölzl and Reinstaller (2000), pp. 5ff.

3.1 The development of a new information system: the accounting revolution from the 1870s to the 1890s

The transformation of the enterprise from a purely productive entity towards the modern large enterprise with complex communication and coordination mechanisms took place gradually in response to a crisis of established management methods due to changes in demand, more complex production technology and problems of co-ordination on the shop floor. Cost control and accounting became a necessity. Cost accounting is a highly interdependent activity. Therefore, the process to achieve an efficient cost accounting information system took place in two overlapping stages. In the first the inside contracting system was replaced by bureaucratic business hierarchies. The second stage saw the transformation of the information processing activities themselves as a response to constraints that were hit by the new information-processing system.

The typical office in the 19th century up to the late 1870s was virtually untouched by technology and consisted of predominantly male workers, a book-keeper, a copyist, a clerk and perhaps a shorthand taker. Clerical work had the characteristics of a craft where necessary skills were acquired on the job and through tutoring by seniors (Cooper and Taylor (2000), Braverman (1974)). Accounting records reflected external market transactions and contained not much information about internal operations. In larger firms, forms of inside contracting were the prevalent method of control. The contracting of internal craftsmen avoided administrative overheads and acted partly "as a substitute for accounting" (Hopper and Armstrong (1991): 415). A large office to process all types of cost and market data was not needed. The manufacturers set their prices on the basis of cost information but were not able to intervene directly in their determination, as they could not co-ordinate the production process.

The reaction to this failure was the Systemic Management movement that gained large support in US manufacturing in the late 1870s (Litterer (1963)). It "based its reassertion of control and co-ordination on record keeping and flows of written information up, down, and across the hierarchy" with the aim to "transcend reliance on the individual in favour of dependence on system" and to monitor and evaluate performance (Yates (1989): 10-11). Systemic Management represented a set of procedures for decomposing activities into elementary work units.³ The decomposition produced cost data, but also information of the exact relationship between work procedures and allowed to introduce standard measures of performance for single activities and sub-processes as well as their parcellation from or integration with others. The first step in taking control of the activities on the

³ Scientific Management that was introduced with moderate success towards the end of the 1890s brought these principles to its limits, Boorstin (1973): 369.

shop floor was the direct payment of wages and salaries. This led to the demise of the inside contracting system. The transfer of authority from foremen to plant managers was gradual. Larger production units supervised by a single foreman were broken up into smaller ones. Tasks like the hiring and payment of workers, material acquisition and performance monitoring were centralised. Thereby the scope of authority of foremen was reduced to the allocation and monitoring of work within small production groups. Parcellation increased the number of foremen and work groups. Many decision tasks were integrated into new centralised staff departments, which acted as an interface between the shop floor and the management. Output requirements were standardized, precise production schedules introduced and the performance could be monitored through detailed cost figures. In this way the management gained direct control (through integration) over the activities on the shop floor. Accounting and its transformation into a current cost management technique were instrumental in this process. The importance of accounting was greatly increased, as it mediated the interactions between the different activities of production and distribution.

The formal bureaucratic structure was the result of a process of decomposition and re-composition which the hierarchy reflecting the information flow of accounting and market data, which in turn reflected the structure of the underlying production problems. The bureaucratic structure was a problem processor that allowed the decomposition of complex decision problems regarding the allocation of resources into sub-problems and at the same time led to a decentralisation of decision-making and a centralisation of ultimate control and co-ordination. But as the information system was set up, new constraints became binding for the information processing activities themselves, as summarised by the following quote from Beninger:

“A crisis of control in office technology and bureaucracy in the 1880s, as the growing scope, complexity and speed of information processing [...] began to strain the manual handling system of large business enterprises. This crisis had begun to ease by the 1890s, owing to innovations not only in the processor itself (the bureaucratic structure) but also in its information creation or gathering (inputs), in its recording or storage (memory), in its formal rules and procedures (programming), and in its processing and communication (both internal and as outputs to its environment)” Beniger (1986): 390.

The large business administrations produced and processed information on an industrial scale. The economic survival of a firm depended on accounting and other administrative activities, which depended on the trained clerks as necessary input. This kind of labour was in quasi-fixed supply. The soaring need for qualified clerks and the low potentials for productivity advances made the constraints set by the labour market for clerical workers binding in the 1880s. In the three decades from 1880 to 1910 the share of clerical workers in total working population increased from 1,1% to

5,1%: the number of clerks in the United States rose from 186.000 to 1.8 million.⁴ These changes in number went hand in hand with the transformation of clerical work and the reorganisation of the office.

[Table 1 about here]

3.2 Finalising the information system: the mechanisation of the administration from the late 1880s to 1930s

The sheer size of the information processing volume and the labour intensive character of clerical activity inflated the bureaucratic structure. The Systemic Management Movement itself had only marginally touched it, even though it was its product. On a smaller scale, these circumstances resembled the situation that had led to the development of the American System of Manufactures four decades before (see Hounshell (1984)). Engineers played an important role in restructuring the bureaucratic machinery (e.g. McPherson (1992)). Their primary objective was to reduce the dependence of administrative processes on skilled clerical labour by making labour and capital good inputs more separable. Their training in the tradition of American engineering provided the background for approaching this problem. The American System of Manufactures can be viewed as a meta-heuristic or problem-solving algorithm for problems in the production sphere. The model was the system of modular production based on standardised parts and activities. This model was applied to the organisation. The division of labour in administrative work was increased through the standardisation of tasks, data and information channels. In parallel, those activities for which this was possible were mechanised. The standardisation of data and tasks was an important precondition for the introduction of office machines, as they could unfold their full productivity potential only if a smooth flow of standardised and indexed information was available.

The role of parcellation and integration in this process becomes clear from the development of bookkeeping practices. Bookkeeping was sliced into a sequence of distinct and specialised occupations. The change in methods, organisation and processes took place gradually. The first step was to separate data handling, which was amenable to standardisation, from data analysis, which was not. Through this the dichotomy of bookkeeping and accounting emerged. Bookkeeping activities were divided into activities of work preparation and activities of data manipulation. Work preparation tasks, such as the sorting of vouchers and receipts and the examination of related

⁴ Compiled from J.M. Hooks *Woman's Occupations through seven decades* US Department of labour 1947 and *Historical Statistics, Abstracts of the US Series D57-71 Later: US Bureau of Census Statistical Abstract (1972)*. For details see Hölzl and Reinstaller (2000), p 8.

ledgers, were executed without mechanical aides, but reached a high degree of specialisation in manpower. In most cases there was one clerk responsible for some subset of tasks with respect to one narrow subclass of accounts. Data manipulation activities entailed the codification, processing and evaluation of data and were supported by mechanical equipment (Pirker (1962): 81-3). Adding machines, calculators, bookkeeping and billing machines or even Hollerith systems were adopted, which were operated by specially trained personnel. The organisation of the accounting activities was turned into a modular system in which improvements or changes in one sub-activity were made independently from changes in other sub-activities. The increased division of labour reclassified clerical work into standardised and quasi-standardised activities.

The re-organisation of administrative work and the invention and development of mechanical devices was a co-evolutionary process. "It was not an accident of fate" (Cortada (1993): 63) that an office equipment industry was built up at about the time when large, multifunctional enterprises emerged by the early 1880s. Most information processing devices were invented and introduced on the market in the years between 1870 and 1890 (e.g. typewriters 1873, cash registers 1879, calculators 1885, Hollerith system 1889). They diffused about ten to fifteen years later on a large scale. The key requirements of the new office machinery were summarised by Leffingwell and Robinson (1950): 282-3): When should office machines be used? To save labour, to save time, to promote accuracy and to relieve monotony.⁵ One could add "in order to achieve an order of magnitude jump in office work productivity". The technical design of these office machines reflected the constraints from which they were born, as they had to be instrumental in realising a system of standardised activities. This is summarised in table 1 for four distinct devices. The critical skills needed to perform quantitative or repetitive operations such as sorting or adding were embodied in some mechanism, and the machines could be operated without much previous training. This led to the saving of labour and increases in productivity, and it was largely independent of the skills of the operators. An embodiment was not possible for more knowledge-intensive activities, such as typing and short hand taking. In these cases office machines were used to support the specialisation of labour. The result of this was a strong complementarity between the new technological artefact and the operator. But the standardisation of the user-interface like the typewriter keyboard also forcibly led to the standardisation of skills and the separability of the process from tacit knowledge or skills specific to a single worker.

Typewriters were the first technology of the new office work regime. Their domains of application were all activities involving the distribution of information on a small scale. The typewriter as a

⁵ These are the headings to sections on machine use in office work.

technical artefact was an innovation but did not in itself represent a productivity-increasing technical advance. Its mechanical construction did not embody any specific clerical knowledge or skills so that its use did not lead automatically to a productivity increase. The crucial criterion for the adoption of the typewriter was its (standardised) human-machine interface. The special interaction of service requirements and technological characteristics that gave birth to the QWERTY keyboard is well known (David (1985): 333). The subsequent development of touch-typing played a crucial role in making the typewriter a viable technology for business administrations, as it contributed to the establishment of a homogeneous labour supply. The co-existence of different keyboards with different practices would have led to a segmentation of the labour market with an inevitably lower elasticity of supply. As typewriters were fixed capital firms organised their operations in such a way as to maximise the rate of utilisation. This led to centralised services for typing, and to functional office departments that pooled typing activities (Leffingwell and Robinson (1950): 34). Typing became a profession and an administrative process in its own right. The typist had a clearly defined activity profile, which consisted of taking (shorthand-) notes and writing them on paper with the machine using a particular typing method. Standards of practice were attained by the standardisation of letter styles and forms, thereby influencing the way business correspondence was done (Leffingwell and Robinson (1950): 143 ff.). Typing pools were formed through the integration of new activities into the administration.

As the large administrative organisations owed their very existence to the attempt to gather and evaluate more quantitative data, the capability to perform simple mathematical operations was of foremost importance. Rationalisation studies carried out at the time showed that almost 60% of all tasks performed in office work consisted of calculations that consisted amounted to 80% of counting and adding (Pirker (1962): 66). Adding and calculating machines were general-purpose tools applicable to a vast range of uses. They embodied the most important skills of a good bookkeeper: quick and reliable computing. The locus of the labour saving potential was primarily the mechanical arithmetic unit, which was independent of the skills of the machine operator. The machines isolated mathematical operations completely from the persons carrying them out. Operators could learn quite quickly to handle them, but did not need to know much mathematics. They did not even need to know a specific standardised method such as touch-typing (see table 1). As documented in table 2, the labour saving effect was in the order of 20:1. Long rows of numbers could be condensed into one single key figure much faster than before. Bookkeeping entered the market in the 1920s. In most cases they were tailored to specific uses and were essentially combinations of an adding machine with a typewriter or just normal adding machines with mechanisms allowing special carriage movements.

[Table 2 about here]

Hollerith machines or tabulating gear differed from the previous technologies. Much more than adding and bookkeeping machines, they were instrumental for the implementation of new organisational designs. This becomes clear if we consider that in order to sell such devices 'a salesman had not to sell the machine but the organisation' (Pirker (1962): 79). Salesmen, who were typically trained engineers, acted as technical advisors as well as organisation designers. The organisational concept developed for businesses in one particular sector was then used as a blueprint (and sale argument) for other firms in that sector (see McPherson (1992)). This was necessary to utilise the capacity of this system at its operational optimum. Tabulating gear was used to process company wide data on a large scale, shifting labour productivity for certain clerical tasks by three orders of magnitude as documented in table 2. Large business firms used these machines to tabulate sales statistics for payroll and inventory management, and later for consumer trend analyses that involved laborious counting and sorting processes.

A tabulating system consisted of punched cards (which were the media on which operating instructions and information were stored), cardpunch machines (which transferred the information on the cards), sorting machines and a tabulator to count the sorted cards. The sorters could be programmed with punched cards on which a sorting routine was codified. This made them very flexible, as they could be re-programmed. The operation of tabulating machines was split into three distinct activities: (i) the codification of sorting and tabulating routines, (ii) the codification of the information and (iii) the evaluation itself, that is the actual sorting and tabulating of information. Accounting and organisation specialists carried out the codification of routines. Specific sorting and tabulating processes were stored on punched cards and could be used when necessary. The programming of routines and routine sequences was an activity that happened only sporadically at the set up of the machine and subsequent organisational changes. These programs made codified procedural knowledge on clerical operations readily available. The codification and evaluation of information were instead recurrent tasks.

Hollerith and Powers systems almost completely isolated productivity increases in data-processing from the skills of the manpower.⁶ The high specialisation and division of labour typical for the shop floor in the American System found its correspondence in a number of new occupations. Pirker

⁶ Exceptions were keypunches. Their efficient operation relied on the speed with which the codification could take place. This first led either to the adoption of the typewriter keyboard (for alphanumeric insertions) or a 10-key keyboard (for purely numerical insertions) with the keys ordered in four rows. Both allowed for the use of touch-typing methods. As the codification of data continued to be the bottleneck in this technology, the use of standardised interfaces was important.

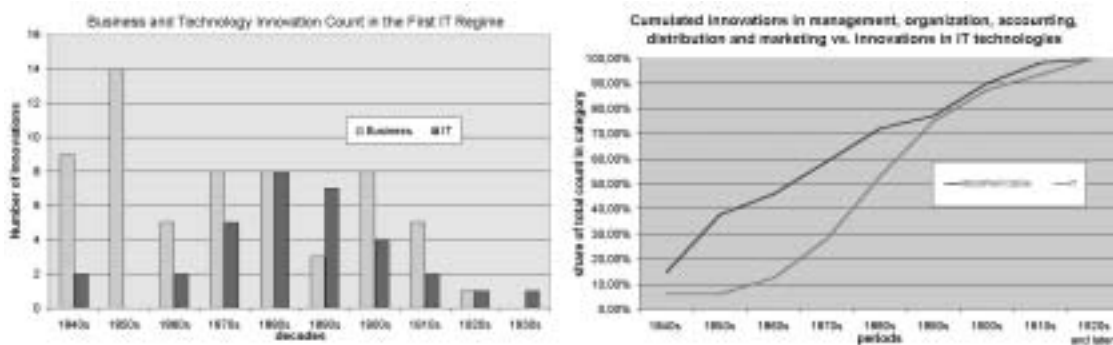
(1962), p. 95, noted in regard to the organisation of work that “for the first time something appears in the office, that can be compared to the working practice on the shop floor”. Key-punch operators codified and controlled the information; sorters were responsible for the supervision of sorting and tabulating processes; lead-machine operators (also called tabulators) were responsible for the wiring of the control panels and the verification of the machines and programmers finally were responsible for the cybernetic part of the job: programming and designing process flows. The skill requirements increased in ascending order: the skill requirements for key-punch operators and sorters were primary school degrees, tabulators needed to have specific technical skills and therefore mostly had secondary school education. The few programmers needed were university graduates in mathematics or engineering, who were considered as professional organisers and operated in a middle management environment (see table 1). Unlike the other professions, the latter were in short supply, but their work was only needed sporadically.

The four technologies presented here were only a small part of a myriad of mechanical devices assuming a fixed place in the organisation of office work, such as billing machines, cash registers, addressing machines, filing systems and so forth.

4. Discussion

What emerges from the historical case study in the previous section is that there were two constraints, which induced interdependent search processes for new technological and organisational designs. The first complementarity constraint was represented by the interdependence of the process generating cost information (accounting), and the process generating business decisions (management). The decentralised organisation of production and the simple accounting system in use during the period of the American System of Manufactures was consistent with the management needs of the time. The system became inconsistent with a larger scale of operations. The change in management practice triggered changes in accounting practice. This is a clear indication for a complementary constraint. Once these organisations were set up, they produced information on a much larger scale, and the problem of efficient processing of the information emerged. The interdependence between production activities and information-processing and management needs led to a second constraint: More information could only be processed with more clerical workers, whose supply was quasi-fixed. This complementarity constraint was internal to information-processing activities and affected the functioning of the entire administrative machinery. As a result, information-processing activities were reorganised and new office machines developed and adopted.

The hypothesis now is that organizational innovations preceded innovations of technological artefacts. The inconsistencies between elements in the administrative process triggered the search for new solutions, a different method of information-processing and new technological artefacts in their support. An innovation count (graph 1), which differentiates between organisational and technological innovations, lends some support to the hypothesis that organisational innovations led to technological innovations and that recombinant search was triggered and guided by complementarity constraints.



Graph 1: Left: Count of important innovations in business strategy and organization and in early information technology. Right: Cumulated innovations.⁷

Graph 1 shows that in the field of information technology some clustering in inventive activity took place in the 1880s and 1890s and was preceded by a large number of innovations in different fields of organisation. Even if the data behind the graph were constructed carefully from a variety of sources, they may suffer some selection bias. These results should therefore be considered with the necessary caution. Nevertheless, the data support the conjecture that technological search and innovation in the field of IT technology were induced by the complementarity constraints emerging from changes in business strategy. The clustering of innovations is the outcome of a directed search process.

The discussion of section 3 showed that the design of the process technology of office work depended on the complementarity constraints that firms faced at the beginning of the process of adaption. The process of decomposition of tasks through parcellation and integration led to a more modular design of the administrative hierarchy. The new machines, which supported information processing, reduced the dependence on skilled clerical work. The number of activities in the realm

⁷ Information on the data is available upon request from the authors. The graphs show innovations that have been classified as important by eminent economic historians. Organisational innovations have to be taken in the widest sense possible: they include new methods of production which induced change in the organisation, such as the introduction of continuous processes, as well as innovations in the field of marketing, accounting and so forth.

of the business administration grew and became more specialised, reflecting the more modular organisational design. In this phase a process of capital deepening and a rise in the capital stock used in the office took place.⁸ The development and adoption of the First IT Regime took place mostly in large firms, so that a significant difference in profitability measures between small and large firms is to be expected. And indeed, as Melman (1951) found for the period between 1899 and 1947, large firms were able to keep their administrative expenditures per dollar of production expense lower than small businesses despite the much more pronounced rise in the administrative overhead. Larger firms benefited more from their use than smaller ones, indicating that scale economies played an important role in the adoption decision. The results of a correlation analysis presented in table 3 suggest that this hypothesis does not only work on the firm level but also on a more aggregate level. The value added (VA) correlates positively with the share of clerks in total staff (A/P) and with the share of office machinery and furniture in total capital ($C_{\text{office}}/C_{\text{total}}$), suggesting that increases in value added were associated with the build up of business administrations. The correlation coefficients are significantly different from zero and their values are close to one. This indicates that firms succeeded in their adaptive efforts to become more competitive through better cost control, which is implicit in the higher share of office workers to total workforce. Simple correlation coefficients are of course no rigorous econometric test. These results should therefore be considered tentative. Better data should alleviate these reservations. Nevertheless, the results suggest that better co-ordination and organisation of the shop floor increased the overall profitability of firms.

[Table 3 about here]

This paper attempted to trace out the nature of recombinant search by providing a framework of inquiry based on the NK model and by studying the historical case of the First IT regime. The case study and the descriptive statistical evidence taken together indicate that the search in the technology space was shaped by complementarity constraints and a response to the changing structure of economic incentives. These constraints were also reflected in the final design of the process technology of modern office work, as the search did not take place in the neighbourhood of the established technique. The observed patterns of technological development lend support to our theoretical conjectures. The results in this paper are of a tentative nature. More detailed research is required to substantiate and generalise these findings.

⁸ By capital deepening we mean the use of more specialised and more productive capital goods.

Table 1: Early information technology: innovation characteristics of the most important technologies of the IT Regime⁹

Technology	User side	(i) Source of productivity gains and (ii) effect on established competences, i.e. clerical work before IT Regime	New professions	Required skills
Typewriter	(i) Co-ordination (ii) Multiplying codifying of qualitative information	(i) User interface, touch typing and complementary technologies (ii) Replacement of copyists	Typist; establishment of typing pools.	Touch-typing (about 60 words a minute), shorthand writing at least 60-75 words a minute (partly replaced by dictaphones), good language and grammar-skills, letter writing ability. High school degree preferred. Training period: approx. 250-400 hours
Adding and calculating machines	(i) Monitoring (ii) Processing of quantitative (accounting) data	(i) Mechanical adding or calculating mechanism, automatic entry controls, user interface (ii) Replacement of mathematical skills;	In large enterprises Comptometer or adding machine operators; used in functionalised bookkeeping, sales or billing departments also on a sporadic base. Establishment of computation pools.	Machine use. Touch-typing. Training period: few days. Girls of about 17 years of age with two years in secondary school.
Accounting machines	(i) Monitoring and allocation (ii) Processing of quantitative accounting data	(i) As for adding machines plus reduction of double entry mistakes through better work preparation (ii) Replacement of book-keepers (mathematical skills, book-keeping skills)	None; used in functionalised bookkeeping departments which took also the form of bookkeeping pools.	Machine use. Training period: accounting clerks with double-entry skills two weeks.
Hollerith – Powers systems	(i) Monitoring and allocation (ii) Processing of quantitative (accounting) data	(i) Electric contact principle, codification of information, sorting and tabulating mechanisms (ii) Replacement of mathematical and statistical skills; sorting and indexing tasks.	Card Puncher Sorter Tabulator Programmer; Establishment of card punch units, and machine rooms.	Puncher: in some cases typing skills, mostly not; primary school degree. No further skills needed. Training period: 1-4 months. Sorter: No special skills, but strong physical constitution required; primary school degree. Training period: about 6 month. Tabulator: secondary school degree and technical skills. Training period: 1,5 to 2 years. Programmer: organisational skills, business skills; preferably university degree in mathematics or a technical discipline. Training period: 4 years.

Source: Hölzl and Reinstaller (2000)

⁹ For information on the source please refer to Hölzl and Reinstaller (2000).

Table 2: Data processing capabilities of early accounting machines round 1926

Type of machine	Information processing capacity ¹⁰ Bit/hour	Current account transactions per hour	Processing speed machine/clerk
Clerk, manual execution	270 (0,03 kbytes)	6	1
Burroughs Adding machine	5400 (0,675 kbytes)	120	20
National Cash Register	6300 (0,78 kbytes)	140	23,3
Smith Premier (typewriter combined with a calculator)	2475 (0,31 kbytes)	55	9,166
Elliot Fisher (typewriter combined with a calculator)	2475 (0,31 kbytes)	55	9,166
Ellis (typewriter combined with a calculator)	5400 (0,675 kbytes)	120	20
Underwood accounting machine	2925 (0,37 kbytes)	65	10,83
Hollerith or Powers card punch machine	6750-11250 (0,84 – 1,4 kbytes)	150-250	25 – 41,6
Hollerith or Powers sorting machine	675000-810000 (84,375 – 101,250 kbytes)	15000-18000	2500 - 3000
Hollerith or Powers tabulating machine	162000-202500 (20,25 – 25,31 kbytes)	3600-4500	600 – 750

¹⁰ We used information contained in Meuthen (1926) for the calculations. We used the figure of a punched card for a current account transaction (p.43) and the table of single cases that could be performed by the single machines (p.48). The following information was stored on the punched card on 45 columns of 10 digits each for one transaction: date of the transaction (6 columns), the number and page of the main register (3+3 columns), the type of the transaction (2 columns), the department (2 columns), the main and secondary number of the current account (5+2 columns), debit and credit (8+8 columns) and finally the day and month of the booking (2+2 columns). The information in each of the 45 columns represents 1 bit (one of the ten rows is punched or not punched). It should be noted, that this is only the information content of the card due to the punches and not the information content if the data would be codified by binary numbers, which is likely to be much higher. We hence calculated the implicit information processing capacity, and not the effective one. We further compare the transactions on the basis of how the most advanced technology (Hollerith: punched cards) of the time codified information. This entails that, with the purely manual system, information was not just written on one single card, but meant filling in fields in several different registers manually, for which a clerk on average needed 10 minutes for one single current account booking operation, Ibid. : 47.

Table 3: Economic effects of the First IT Regime in US manufacturing: correlations.

	Total period: 1889-1937	Subperiod
VA to A/P	0.685**	0.975*** (1899-1919)
VA to C _{office} /C _{total}	0.762**	0.858* (1899-1919)

Source: Reinstaller and Hölzl (2001), they provide a detailed account on datasources and definitions.

*** statistically significant at the 1% level, ** statistically significant at the 5% level, * statistically significant at the 10% level

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