Eindhoven Centre for Innovation Studies

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The Evolution of Tank Technology, 1915-1945

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Working Paper 06.02

Department of Technology Management

Technische Universiteit Eindhoven, The Netherlands

January 2006

‘Chariots of Fire’: The Evolution of Tank Technology, 1915-1945

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THIS VERSION: DECEMBER 2005

We revisit the notion of technological trajectories by means of a detailed case-study of the evolution of tank technology between 1915 and 1945. We use principal component analysis to analyze the distribution of technological characteristics and how they map into specific service characteristics. We find that, despite the existence of differences in technical leadership, tank designs of different countries show a high degree of overlap and closeness along a common technological trajectory. In the conclusions, we speculate on whether this pattern can be explained by common heuristics that influenced the rate and direction of design activities or by doctrinal viewpoints influencing the development and use of tanks on the battlefield.

Keywords: Technological trajectories, Technological paradigms, Tanks.

An earlier draft of this paper has been presented at the fourth European Meeting on Applied Evolutionary Economics (EMAEE), Utrecht, May, 2005. We thank the participants at the meeting for helpful comments. In particular, the paper has benefited from the suggestions of Jerry Silverberg, Marco Valente, Werner Holzl. We also thank Giovanni Dosi and Bart Verspagen for encouraging words and useful discussions. Usual disclaimers apply.

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1. Introduction

The notions of technological paradigms and technological trajectories have exerted a wide appeal among economists and other social scientists working in the field of innovation studies. Since the seminal contributions by Dosi (1982, 1988),[1] several authors have devoted substantial efforts to provide detailed empirical analyses of the process of technical change employing this framework (see, amongst others, Sahal, 1985 and Saviotti, 1996). Besides these authors however, most of the literature has adopted the notions of paradigms and trajectories in a rather loose way, mainly as metaphors featuring in broad ('appreciative') reconstructions of the patterns of technological evolution.

The main aim of this paper is to re-visit the original potentialities of Dosi's framework in a detailed case-study of the evolution of a specific technology. In particular, we present an historical study of the evolution of tanks for the period 1915-1945. Tanks represent one of the major innovations in military technology introduced in the first half of the twentieth century and the history of their development presents several points of interest in its own right (Hacker, 2005). However, we contend that from our case study one could also draw broader implications with general bearings for the innovation studies literature. The tank - at least in the period we consider - constituted a complex engineering product aimed at achieving certain performance results (in most general terms: mobility, firepower and protection). The task of tank designers was to search for technical solutions that translated into acceptable performance levels. In the case of tank technology, the relationship between the configuration of the various technical characteristics of the tank (road speed, armour, armament calibre, etc.) and the performance attributes is relatively straightforward. However, the existence of interdependencies among technical characteristics produced a number of trade-offs between performance attributes. In order to develop 'good' designs, engineers had to search for 'satisfying' solutions. Hence, the particularly clear-cut nature of the engineering trade-offs characteristics of this technology provides an ideal starting point for the study of the technological trajectories and of the underlying search processes. Secondly, in the period considered, for obvious strategic motives, all the major industrialized countries were engaged in the development of tanks. In this early phase, as stressed by the received historical accounts of the evolution of tank technology (Murray,

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[1] An earlier formulation of the idea of 'technological paradigm' was put forward by Constant (1973).

1996), it was not at all clear what would have been the most effective way of employing tanks on the battlefield. Different countries held drastically different viewpoints on this topical issue. In the 1920s and 1930s, military establishments in France, UK and USA tended to regard the tank simply as a "gun with a certain degree mobility" to be primarily employed for infantry support. In Germany, mainly due to the influence of Heinz Guderian (Guderian, 1999), tanks were instead considered as the backbone of new tactics based on speed and mobility. Therefore, it will be of particular interest to examine to what extent the debate among these different doctrinal viewpoints influenced the rate and direction of design activities.

The paper is structured as follows. In section 2 we discuss the major theoretical and empirical issues related with both the identification and the mapping of technological trajectories. Section 3 presents our data-set and provides a short historical account of the main trends in the evolution of tank technology. In section 4, following Saviotti and Trickett (1992), we use principal component analysis to study the distributions of technological characteristics of the tank models contained in our data-set We employ Standard Deviational Ellipses technique to map the evolution of tank trajectory. In Section 5 we discuss the main findings of our exercise and conclude.

1. Background literature

As it is well known, Dosi (1982, 1988) proposed what may be called a paradigm/trajectory approach to the study of technical change. Dosi defines a technological paradigm as: "model and a pattern of solution of *selected* technological problems, based on *selected* principles derived from natural sciences and on *selected* material technologies" (Dosi, 1982: 152, italics in the text). The term paradigm is clearly borrowed from Thomas Kuhn's philosophy of science. In the case of technologies, the concept of paradigm refers to a framework, jointly adhered by a significant group of innovators, guiding the search for technical advances in particular historical contexts. In this way, a technological paradigm defines the boundaries of the domain in which future technological developments will take place. Dosi suggests that it should be possible to deconstruct each technological paradigm in a set of "heuristics". These represent the prevailing accepted rules prescribing the procedures to be adopted in the search for innovations (for example: "in order to develop a more efficient steam engine, try to increase the rate of expansion"). It is interesting to note that the notions of technological paradigms and heuristics are intended to be broader in their scope than mere sets of engineering prescriptions. In Dosi's view, technological heuristics are the product of the "amalgamation" of what might be termed the "autonomous drift" of a technology (i.e. the "compulsive sequences" of challenges and solutions identified by Rosenberg (1976) which are insensitive to market signals) with "inducement factors" of a genuine economic nature (i.e. current and expected factor prices). This means that local circumstances can, to a certain extent, shape the pattern of technological development.

> The heuristic search process practised by the inventors' community generates relatively ordered patterns of technical change, called "technological trajectories", by channelling inventive activities into specific and finalised directions. These trajectories can, at least in principle, be mapped in both the space of input of coefficients and that of product characteristics (Dosi, 1997: 1533).
>
> The paradigm/trajectory view of technological evolution points to three essential features of the process of technical change:
>
> i) the *local* nature of technical progress: inventive activities are paradigm-bounded and, for this reason, they are highly selective and focussed in rather precise directions;
> ii) along a specific technological trajectory, technical advances are strongly *cumulative*, that is to say, they are strongly related to previous attainments;
> iii) technological development is likely to display strong *irreversibility*. This means that techniques developed along particular trajectories are likely to become superior to old ones at every relative factor price level. As a consequence, once the movement along a particular technological trajectory has gained momentum, it becomes relatively irresponsive to changes in input prices.

One of the appealing features of the paradigm/trajectory view was that it could provide a theoretical explanation for a number of empirical findings (mostly going under the heading of 'technological forecasting') that since the late 1970s and early 1980s had introduced and developed quantitative indicators to describe the evolution of technologies.[2] These studies revealed that the evolution of technologies was characterized

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[2] For good overviews of the achievements of this literature, see Sahal (1981), which contains a collection of essays published during the late 1970s, Saviotti (1988), and the special issue of *Technological Forecasting and Social Change* (1985, **27**, 2-3).

by relatively ordered dynamics of 'progress' in the various characteristics space in which they could be mapped. Furthermore, these patterns were also punctuated by discontinuities and ruptures that could be linked to historical episodes of paradigm change. As Dosi puts it:

> "[T]here is no a priori economic reason why one should observe limited clusters of technological characteristics at one time and ordered trajectories over time. Indeed, given consumers with different preferences and equipment users with different technical requirements, if technology had the malleable attributes of information and if innovative search were a purely random search process, one would tend to observe sorts of "technological indifference curves" at any one time and, over time, random search all over the n-dimension characteristic space….[Rather,] the evidence surveyed suggests that one still observes "explorations" limited to some, smaller subsets of the notional characteristics space. It is precisely the paradigmatic cumulative nature of technological knowledge that accounts for the relatively ordered nature of the observed patterns of technological change." (Dosi, 1988: 1129)

Somewhat paradoxically, however, precisely when the times seemed ripe for establishing an intriguing link between theoretical developments and empirical evidence, research efforts aimed at producing a detailed quantitative mapping of the long term evolution of technologies began to peter out. At the same time, since the late 1980s, growing concerns for providing 'contextualized' interpretations of technological evolution rendered also the field of the history of technology impermeable to exercises in measurement and quantification.

One major exception is the stream of literature initiated by Saviotti and Metcalfe (1984). Saviotti and Metcalfe (1984) built an explicit link between the construction of technological output indicators and the concept of technological trajectories. In their representation of technology, they draw an important distinction between 'technical' or design related characteristics and 'service' characteristics. Technical characteristics represent the internal structure of the artefact and, in most cases, are the dimensions that designers take into consideration (for example, in the case of the car, type of engine, type of suspensions, weight, etc). Service characteristics, instead, are the 'services' actually delivered by the artefact in which users are interested (in the case of the car, speed, reliability, comfort, etc.). Saviotti and Metcalfe (1984) note that, in general there is no one-to-one mapping between technical and service characteristics. Rather, in most artefacts one technical characteristic will typically affect several service characteristics through a complex pattern of correspondence.

This conceptual framework has obvious implications for the mapping of technological trajectories. Indeed, one has to be well aware whether observable modifications in the artefact result from changes in the design space, service space or in transformations in the pattern of mapping between the two (Saviotti and Metcalfe, 1984: 144-148).
However, to date, there have been scarce attempts to analyse the evolution of individual technologies using this framework, namely Saviotti and Trickett (1992) for helicopters, Frenken *et al.* (2000) for aircrafts, Frenken and Nuvolari (2004) for steam engines, and Frenken (2005) for microcomputers and laptops.

This paper expands on this research tradition. Its aim is twofold. First, it provides a new case study of a technology within the Saviotti and Metcalfe framework. Second, relying on the distinction between service and technical characteristics, it aims at assessing the driving factors underlying the dynamics of technological trajectories. In particular, our purpose is to disentangle the role of what may be called "technological imperatives" stemming from the nature of the internal structure of the artefact, as distinguished from the influence of various contextual factors.

3. The development of tank technology: a short historical overview

This section takes a first glance at the development of tank technology. First we present our data source. Then we give a short account of the main technological events that characterized the history of tank technology in the period in question. Both sections provide the preliminary background for the analysis that follows.

3.1 The Data

Our main source of information for the analysis presented in this paper is a dataset of 262 tank models manufactured between 1915 and 1945. This dataset has been constructed on the basis of the information contained in Hogg (2000) a directory of all tanks ever built between 1915 and 1999. We consider a sample of five major industrialized countries: France, Germany, URSS, UK and USA. For each model, the dataset reports information on several technical characteristics of tanks such as, width, hull length, height, weight, armour thickness, road speed and range, armament calibre as well as year of production and the manufacturer(s). Additional information on quantity produced and the period of service of each tank model has been collected from various historical sources. Figure 1 below reports the number of tanks models present in our sample. The number of designs experienced a sharp rise towards the end of World War I (WWI), a decrease in the years that immediately followed the end of the conflict and a steady increase from 1923 onwards as a consequence of the proliferation of models that characterised the race toward rearmament.

[Insert Figure 1 approximately here]

In Table 1 below, the number of tank models is broken down by country and time periods.

[Insert Table 1 approximately here]

It can be noted that, against an overall pattern of increase, various countries behaved differently. The UK is the country with the highest number of models manufactured, followed by the USA and Germany. UK, France and USA are the leaders during WWI while the USSR did not manufacture any tank until the 1920s. Between 1920 and 1930 Germany introduced only one tank, a prototype that never went into full production. This was a consequence of the ban on army production imposed by the Versailles Treaty that delayed the diffusion of this new weapon in the country. This delay notwithstanding, Germany caught up very rapidly during the 1930s with the highest number of tank models among the countries in our sample. Model proliferation continued between 1940 and 1945 for all countries with the obvious exception of occupied France.

3.2 Milestones in the evolution of tank technology

Although the idea of armoured fighting vehicles had been circulating for long time (one could actually trace the concept to the horse drawn chariots launching spears and arrows that were employed in the Near East as far back as 2000 BC), it was only during WWI that the three key mechanical constituents of the tank: bullet proof armour, internal combustion engine and caterpillar tracks, were available. Their combination turned out to be crucial for breaking the circumstances of the deadlocked trench warfare of attrition on the western front. Accordingly, the date of birth of tank technology can be put in 1917 when tanks were first employed on the battlefield in sizable numbers although early designs and prototyping began in 1915.[3] Figures 2 (A, B, C) illustrate the development of the technology by charting the progress over time in the three fundamental technical characteristics: armament calibre, armour thickness and road speed. The figures show the models that can be considered as 'milestones' with labelled markers (markers without labels represent other noteworthy designs, although of somewhat minor historical significance). The figures also contain a time trend line which is computed using *all* the models contained in the dataset.

[Insert Figures 2 (A, B, C) approximately here]

The history of our technology can be usefully sub-divided in the 4 main periods: WWI (1915-1920), the 1920s (1921-1930), the 1930s (1931-1939) and WWII (1940-1945).

Tanks produced during WWI were characterized by a rather low degree of mobility (the maximum road speed was less than 10 km/h and range was fairly limited). The minimum requirement for the armour was obviously to provide protection against machine-gun fire, whereas fire power capabilities were ensured by fitting into the vehicle guns of calibre comprised between 20 and 40 mm (the two most representative models, in this respect may be considered the British 'Mother' with its typical rhomboidal shape and the French Renault FT-17, which was the first tank with a rotating turret). During the war, these types of tanks proved capable of successfully piercing enemy's trenches. However, low speed prevented them from achieving deep breakthroughs beyond enemy lines. In this first period there were also experimental attempts of mounting heavy guns on tanks. This was done in the French Char 2C mounting a 75 mm gun and in the German K-Wagen mounting 77 mm guns. Interestingly enough, such heavy guns will be fitted again into tanks only from the late 1930s. In fact, the sheer weight of these machines greatly limited their effectiveness. In the end, only 10 Char 2C and 2 K-Wagen were actually built.

Design efforts during the 1920s aimed at solving a number of limitations related to the general operability (not least the extreme crew discomfort of WWI models) and to the overall mobility of the machine. Accordingly, in this period some teething shortcomings were solved and the single rotating turret design emerged as the most effective solution.

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[3] This short historical overview of the evolution of tank design draws heavily upon Ogorkiewicz (1991).

As shown in the figures, Britain was the most active country in this phase. A particular noteworthy tank of this period was the Vickers 6-ton, which was produced by Vickers as a private venture. The tank was not adopted by the British Army, but a very similar design (the Vickers medium A6) was employed. However, the development of this tank led to a more favourable view of armour warfare in the military establishments of various countries (Habeck, 2003). Indeed, the Vickers 6-ton was purchased by several countries and its design was copied in Russia providing the basis for the early development of Soviet armour.

The 1930s witnessed a growth in the number of designs introduced (obviously linked with the rearmament race). The most successful tank of this period was probably the Russian BT-5 which employed the independent suspension system invented by the American engineer J. W. Christie. It also featured an unprecedented high power/weight ratio that provided a major breakthrough in road speed (65 km/h) and mobility. A 47mm gun was fitted on the tank. Other tanks representative of this period are the French R-35 (a 'light' tank fitted with a 37 mm gun) and the British Matilda 2. This tank, although slow (25 km/h), was endowed with thick armour (78mm) and had a 76mm gun. The figures show that many representative tank models introduced during WWII mounted similar calibres.

The WWII period was a phase in which design activities had, obviously, to take into account the feedback stemming from the relative performance of various models in the battlefield. The figures show a number of models with gun calibre around 75mm or 76mm (the German Panzer 4, the Soviet T-34, the American M-4 Sherman, and the British Churchill). In a slightly later phase, we see a clear attempt to fit even higher gun calibres (88mm for the German Tiger, 85mm for the Soviet T-34 and 90mm for the American M-26, up to the 122mm of the Soviet JS). There is a somewhat wider dispersion in armour thickness, although it is evident also in this case that tank models of different countries tended to converge towards similar values. This behaviour can be plausibly interpreted by the need of matching the battlefield capabilities of enemy models. The most successful design of the WWII was the famous Russian T-34, which probably represented an almost ideal combination in terms of speed, armour thickness and gun calibre. Compared to the Panzer 4, the dominant German tank, the T-34 was clearly superior in all three technical characteristics. The appearance of the T-34 stimulated the Germans to introduce the Panther and the Tiger, designs endowed with more powerful guns and thicker armour. However, it is worth noting, that, although seemingly qualitatively superior, these tanks were produced in lower numbers. The most famous American tank of WWII was the M4-Sherman. Born as an attempt to match the calibre of the German Panzer 4, this tank was fitted with a 75mm gun. The M4 did not match tanks such as the Tiger and the T-34 in armour thickness. Together with the T-34, the M4 is the tank that was produced in largest numbers during WWII.

Representing tanks on the basis of their technical characteristics alone provides just a rough sketch of the historical developments in tank designs. Indeed, tanks are not simple bundles of technical characteristics. In each design technical characteristics are inter-related with each other to form what Saviotti and Metcalfe (1984) define as the "internal structure of the technology". Furthermore, there is a complex pattern of mapping between technical characteristics and service characteristics. This set of interactions is likely to present designers with a number of trade-offs. Ultimately, a good design is a particularly well chosen compromise between the trade-offs existing in a specific technological domain. The aim of the following section is to provide an assessment of the linkages between technical characteristics and of the patterns of mapping between these and service characteristics. This exercise will provide insights into the search process which characterized the historical evolution of tank technology.

4. The empirical analysis

In this section we move forward in the analysis of the factors affecting the trajectory of tank technology. We proceed in two steps. First, we position the case of tanks within the framework of analysis based on the distinction between service and design characteristics proposed by Saviotti and Metcalfe. Second, we employ principal component analysis to study the evolution of tank models over time.

4.1. Conceptualising tank technology

A tank is a technological system whose design is a compromise between different service dimensions which, in turn, are affected by several technical characteristics. Miller (2002: 6) identifies three main service dimensions: firepower, protection and mobility. Firepower and protection refer to the services tanks deliver on the battlefield. They both define the 'battlefield capability' of the artefact. Tank mobility instead is important in different contexts not only on the battlefield. Accordingly, Ogorkiewicz (1991: 223) distinguishes between three different kinds of mobility: strategic mobility (i.e. the ability of tanks to be moved into the area of operation), operational mobility (i.e. the ability of tanks to move in the area of operation) and battlefield mobility (i.e. the ability of tank to move when in imminent contact with the target). Each of these services is usually influenced by more than one technical characteristic. Figure 3 below provides a conceptualisation of the relationship between technical and service characteristics.

[Insert Figure 3 approximately here]

Technical characteristics are listed on the right hand side, while service characteristics are summarised on the left hand side. It can be noted that there is no one-to-one mapping between the two spaces. To improve one specific service, designers could work on several technical characteristics. This is especially true in the case of mobility. For instance, strategic mobility involves travelling considerable distances to the fields of operation. The ease and speed at which distances can be covered by alternative means of transport (rail, ships and/or roads) depends inversely on the weight and size of the tanks (the width was particularly influential as long as transport occurred mainly by rail during WWI and II). Battlefield mobility instead involves the capability of tanks to move in quite different terrains ranging from soft soil to hard ground. To the extent that mobility depends on the pressure exerted on the ground, battlefield mobility on soft soil depends inversely on weight. Battlefield mobility on hard ground depends instead on how the weight of tank is distributed which in turn depends on the type of suspensions implemented and on the length of the tank. Suspensions can help reducing ground pressure. Increasing the length of the tank can help distributing better its weight on the wheels. In both cases, mobility is increased. Finally, operational mobility involves the ability of tanks to move under their own power along roads as well as cross country. Cross country movement is inversely influenced by the weight of tanks. Heavy tanks are generally slower than light ones because they exert higher ground pressure. Road speed, range and engine power instead positively affects movement. Range, defined as the average distance a tank can cover without requiring any logistic support, seems particularly important for operational mobility. The wider the range, the higher the freedom of movement becomes.

Understanding the link between technical and service characteristics does not exhaust all the issues involved in tank design. Indeed, the complexity of tank design is in part due to the presence of interdependence among the technical characteristics themselves. To improve performance, designers had, and still have today, to engineer around several technical trade-offs. Consider mobility for instance. Increasing the length of the tank improves operational mobility. However, longer tanks become heavier and less manoeuvrable on the battlefield which increases the probability of being hit. In the case of operational mobility, range can be increased by reducing the frequency of refuelling through an increase in the amount of fuel that can be carried. However, carrying extra fuel increases the weight of the tank which further increases the demand of fuel especially if tanks are powered by gas turbines instead of more efficient diesel engines. Finally, technical trade-offs very often translate into service trade-offs. For instance, better battlefield capability (i.e. better protection and greater fire power) achieved through an increase in armour thickness and higher armament calibre leads to an increase in the weight of the tank and a decrease in road speed. Battlefield capability is improved at the expense of mobility if it is not supported by an improvement in another characteristic such as engine power for instance.

As argued in Section 3, the evolution of tank technology between 1915 and 1945 was characterised by a common heuristics entailing an increase in road speed as well as in armour thickness and calibre. Evidence on the major trade-offs between technical characteristics that accompanied the evolution of tanks is presented in Table 2 which reports the Spearman correlation ranks for selected pairs of technical characteristics.

[Insert Table 2 approximately here]

As expected, the coefficient signs indicate that trade-off existed only for certain characteristics (notably road speed and armour, road speed and calibre). The trade-offs became particularly important during the 1940-45 time period when countries tried harder to tackle them. Coefficients show that certain countries, notably Germany, succeeded in solving the trade-offs better than others (USA). Armament calibre and armour thickness are positive correlated. This result confirms that pursuing greater fire power and looking for better protection occurred in parallel and became relevant during WWII when the armament race intensified. All in all, the size of the coefficients suggests that, despite the existence of a common heuristic, countries seemed to differ in its implementation. Next section aims at gaining a better understanding of the reasons underlying these differences.

4.2. The principal component analysis

Following Saviotti and Trickett (1992), we use principal component analysis to study the distribution of technological characteristics in our population of tank models. Principal component analysis is a widely used method of data reduction. When it is applied to an original set of variables, it creates a new set of variables that are correlated with the initial ones and that explain a reasonably high percentage of the variance existing in the sample. In this way, the behaviour of the initial set of variables may be usefully summarized by the behaviour of the principal components. Table 3 and Table 4 report the results of our principal component analysis.

[Insert Tables 3 and 4 approximately here]

The initial set of variables comprises: weight, road speed, range, engine power, armour, and armament calibre. Other important variables (i.e. width, hull length, height, type of fuel, type of suspensions, armour slope, etc.) were not included because they were not available for a sufficient number of models. Historical studies have pointed to the critical role of other characteristics, such as reliability or component standardization, in affecting the overall performance of the tank, but these are hard to pin down using quantitative indicators.[4]

Eigenvalues are shown in Table 3. The so-called Kaiser criterion (Kaiser, 1960) suggests retaining only those principal components with eigenvalue greater than 1. Accordingly, in our analysis we limit ourselves to consider the first two principal components. Table 4 reports the eigenvectors of the components. The eigenvectors are the weights of each initial variable for each principal component (each principal component is a linear combination of the initial set of variables). It is worth noting that we have considered in our analysis only tanks produced in more than 5 exemplars, as a way to limit the influence of outliers and experimental designs in our reconstruction of the patterns of

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[4] Indeed, when this larger set of characteristics is taken into account, the assessment of the relative performance of tanks designs becomes much more difficult and debatable. See, for instance, the discussion contained in Johnson II *et al.* (2000).

technical change. However, we have computed the values of the principal components also for models produced in less than five exemplars, in order to see their position with respect to the core of our technological population.

Table 3 shows that the first two principal components account for more than 80% of the total variance. Our first principal component (PC1) contains high contributions from weight, engine power, armour and armament calibre, whereas road speed and range contribute less. Our second principal component (PC2) is characterized by strong contributions of road speed and range and by small or even negative contributions from the other variables. In terms of interpretation, PC1 may be clearly understood as an indicator of the overall battlefield capability of the tank (in particular PC1 may be viewed as a synthetic indicator of fire-power and protection), whereas PC2 appears as an indicator of mobility. It should be noted that the results of the principal component analysis are robust to the inclusion or exclusion of other variables in the initial set of variables analysed.

The estimated principal components can be used to evaluate the relative merits of alternative tank designs. Figures 4 (A, B, C, D) represent the distribution of our tank population in terms of principal components in various sub-periods. Superior designs are located farther in the North-East region of the principal component space.

[Insert Figures 4 (A, B, C, D) approximately here]

A similar cross-country pattern seems to emerge. In the early period 1915-1920, tank designs are concentrated in the South-West region and display negative values of both PC1 (battlefield capability) and PC2 (mobility). In the period 1921-1930 there is a movement towards the right, which can be interpreted as an attempt to improve the mobility of the tank. In the period 1931-1939, tank designs are mostly clustered on a diagonal around quadrant II and IV of the principal components space.[5] Finally in the final period, 1940-1945, we see the cloud of designs moving in a North East direction, with several tank models characterized by positive values of both PC1 and PC2.[6] It is

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[5] The few tank models in this period that are able to 'score' positive value of both PC1and PC2 are Soviet tank models.

[6] Among these models we find some of the most successful tanks such as the Russian T-34 and the German Panther, together with the British Cromwell which is not usually regarded as particularly effective design because of the lack of slope armour, a feature not considered in our principal component analysis.

interesting to see that some experimental 'super-heavy' tank models such as the German Maus and E-100 as well as the American T-28 are located far away from the region which contains the majority of tank designs. These models clearly represent 'aberrations' with respect to the normal pattern of technical progress.[7]

As we have noted in the previous section, it would be misleading to limit the consideration of the effectiveness of various tank models only to the evaluation of technical characteristics. During WWII, being able to mass produce tanks was, from a strategic viewpoint, at least as important as improving their quality. Table 3 contains the quantities and the principal component values of the main tank models used during the war.

[Insert Table 3 approximately here]

While good designs could not always be easily mass produced, in some case (notably the T-34 and the M-4 Sherman model), this was indeed possible.

4.3. Mapping the technological trajectory

The results of our principal component analysis provide insights into the nature of the search process that underlay the evolution of tank technology. Consistently with the paradigm/trajectory approach, our finding suggests that inventive activities were selective and finalised in rather precise directions. Figure 5 maps the unfolding of the technological trajectory in our space of Principal Components, by means of subsequent "Standard Deviational Ellipses" (SDE).

[Insert Figure 5 approximately here]

The construction of SDE is a technique for analysing dispersion in point patterns in two-dimensional spaces (see, Ebdon, 1977: 112-119, for a detailed overview). SDE are fitted by calculating: the centre of the ellipsis, the orientation, and the length of the shortest and longest axes, which are always orthogonal to each other. Specifically, the centre of

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[7] Indeed, in the case of Germany, the presence of such 'aberrations' is revealing of a general approach to tank design based on the idea of constructing the "miracle tank" (i.e. a tank endowed with unparallel armour and armament). The Tiger may be considered as a rather successful outcome of this approach (see Johnson II *et al.*, 2004: 247)

the ellipsis is simply the mean centre of the point pattern, the orientation is given by the calculation of the direction of maximum dispersion, and the length of the two main axes reflect the dispersion of the points around the centre along those dimensions. For each sub-period of our sample, we construct one SDE. The arrows connecting the centres of two subsequent ellipses provide a synthetic representation of design shifts and describe the unfolding of the trajectory. This technique seems to provide a rigorous implementation of the idea of representing the path of evolution of a product population through aptly defined clusters of points as proposed by Saviotti (1996: 67-70).

Between the first and the second period, the ellipsis shifts horizontally suggesting that there is an attempt at improving the mobility of the tank, somewhat neglecting the battlefield capability. Between the second and the third period, efforts to improve battlefield capability were carried out, without sacrificing too much on mobility. This led to a cluster of tank models stretched diagonally along region II and IV in the principal components space. The stretching of the cluster can also be interpreted as a process of specialization of tank designs. In this sense, countries dealt with engineering trade-offs not only by means of design improvements but also by producing models with different capabilities. This is the main motivation for the emergence of the differentiation between 'light', 'medium' and 'heavy' tanks. Between the third and the fourth period (i.e. during WWII) we see a further shift toward the North East area of the graph with some particular successful models capable of scoring good combinations in both mobility and battlefield capability. Not surprisingly, the war seems to have induced an acceleration of technical change. This development is not only related to the increase in the resources invested in development of new designs, but also to the feedback generated by the actual use of tanks on the battlefield (as well as to the reverse engineering on captured enemy models).

By looking at Figures 4 and 5 together, another interesting finding emerges. Although there were particularly successful designs, there was also a rather high degree of closeness and even overlap between tanks produced in different countries. In this sense, no country seems to have ever gained a sizable and sustained technological leadership. This result contrasts with widespread beliefs in the superiority of German tanks that circulated in many Allied military circles in the initial phases of WWII. In the North African front, this belief even led to the formulation of a rule of thumb which stated that in order to approach combat with some victory chances, British tanks ought to have a numerical superiority of at least 3 to 2 (Griffith, 1990: 74). As suggested by several historians (see Harris, 1995 and the essays collected in Harris and Toase, 1990), the successes achieved by German tanks in the first years of the war were due more to their effective use on the battlefield than to an intrinsic technological superiority. The same holds true for the Soviet achievements after 1942.

5. Discussion and conclusion

This paper has taken an empirical stance to study the notion of technological trajectories. By looking at the evolution of tank technology between 1915 and 1945 principal component analysis and Standard Deviational Ellipses techniques have been used to analyze the distribution of technological characteristics and to map them into specific service characteristics. Despite the existence of differences in technical leadership across countries, we have found the presence of a high degree of overlap among the tanks designs of different countries and we were able to identify a common technological trajectory.

These results raise a series of issues related to the application of the paradigm/trajectory view in empirical studies of technology evolution. The first issue concerns the interaction between different types of knowledge that shapes the trajectory. Dosi's notion of paradigm is essentially restricted to a community of technological practitioners. However, in the case of tanks, doctrinal aspects (i.e. the theory of 'blitzkrieg' developed by Guderian and the analogous concept of 'deep battle' due to the Russian Tukhachevskii) mattered for the development of the technology.[8] Indeed, the case of tanks has suggested that at least two communities were interacting and potentially shaping the evolution of the trajectory. The first is the community of engineers involved in design activities. The second is the community of military establishments and strategists engaged in the formulation of the 'principles' on how tanks were to be used in the battlefield. Interestingly enough, historians have so far devoted most of the attention to the paradigmatic discussion taking place within this second community. In particular, several contributions have focussed on the one hand, on the failures of 'innovative thinkers' such as J.F.C. Fuller and Liddell Hart in transforming the views of the British military

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[8] Following the execution of Tukhachevskii in the 1930s, the concept of 'deep battle' was rejected from high command of the Red Army. However, after the initial dramatic defeats Soviet military establishments quickly returned on their footsteps.

establishment on the role of tanks in future wars, [9] and, on the other hand, on the successes of Guderian and Tukhachevskii in developing successful principles of tank operation in Germany and the Soviet Union. To date, instead, there has not been much research devoted to the engineering community.

In this respect, there are two particular important implications for scholars interested in the application of the paradigm/trajectory approach to the history of technology. The first, which is in line with current developments, is that due attention must be paid to users and the communities in charge of prescribing the 'code of use' of a specific technology. In most cases, this means that it may be necessary to adopt broad narrative frames spanning beyond the study of the activities of the community of technological practitioners (Edgerton, 1999; Staudenmaier, 2002). The second point is that quantitative studies such as the present one can help in shedding light on the role played by various communities in shaping technical progress along specific directions. Our reconstruction reveals that the pattern of technical change in tank technology in the period 1915-1945 was broadly similar in all the countries we are considering. This clearly points to a relatively minor influence of doctrinal debates on actual tank designs, although not on their use on the battlefield.

The second issue is methodological. This paper has shown that technological trajectories can be studied by using data on the technical characteristics of artefacts. A number of recent studies (Mina *et al.*, 2004; Verspagen, 2005) have attempted to map technological trajectories using patent data. These contributions reconstruct the knowledge flows underlying the development of specific technologies. Indeed, knowledge can be regarded as a further space in which the dynamics of technical change takes place. In this sense, this approach is complementary to the mapping exercises on technological and service characteristics carried out in this paper. Providing quantitatively-based accounts of technological change which integrates the knowledge, technological and service characteristics space is the challenging research agenda for the future.

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[9] The following statement by Sir Douglass Haig (commander of one of the two armies of the British force on the continent during WWI and one of the most enthusiastic supporter of mechanized warfare) in 1925 is revealing of the degree of doctrinal conservatism existing among British high command: "I believe that the value of the horse and the opportunity for the horse in the future are likely to be as great as ever...I am all for using aeroplanes and tanks, but they are only accessories to the man and the horse, and I feel sure that as time goes on you will find just as much use for the horse – the well-bred horse - as you have ever done in the past" (cited in Smithers, 1986: 249-250).

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List of Tables

Table 1: Number of tank models by country and time periods

	1915-1920	1921-1930	1931-1939	1940-1945	TOT
France	7	6	17	1	31
Germany	5	1	21	31	58
USSR	-	3	16	13	32
UK	14	22	20	20	76
USA	7	10	19	29	65
TOT	33	42	93	94	262

Table 2: Spearman's Correlation rank for selected technical characteristics

	Armour / Calibre				
	15-45	15-20	21-30	31-39	40-45
Germany	.52***	.33	nc	.54**	.75***
USSR	.84***	--	nc	.68**	.86***
UK	.50***	nc	.01	-.25	.57**
USA	.79***	.27	.84***	nc	.81***
France	.26	.26	.72	.50*	--

	Road Speed / Armour				
	15-45	15-20	21-30	31-39	40-45
Germany	.17	-.41	nc	.07	-.45**
USSR	-.16	--	.87	-.37	-.14
UK	-.01	.01	.31	-.57**	-.33
USA	.22*	.41	-.36	-.25	-.74***
France	.06	.58	.50	-.54**	-

	Road Speed / Calibre				
	15-45	15-20	21-30	31-39	40-45
Germany	-.36**	-.82	nc	-.60**	-.44**
USSR	-.14	--	.87	-.61**	-.47
UK	-.20	nc	-.29	-.05	-.18
USA	.11	.50	-.41	nc	-.65***
France	-.24	.08	.77	.26	--

*** Denotes significance at 99% level, ** Denotes significance at 95% level, * Denotes significance at 90% level; -- No observations; nc Not computable

TABLE 3A: PCA EIGENVALUES

COMPONENT	EIGENVALUE	PROPORTION OF TOTAL VARIANCE EXPLAINED	CUMULATIVE PROPORTION
1	3.20770	.5346	.5346
2	1.66435	.2774	.8120
3	.44653	.0744	.8894
4	.38503	.0642	.9506
5	.22831	.0381	.9887
6	.06810	.0113	1.0000

TABLE 3B: PCA EIGENVECTORS

VARIABLE	1	2	3	4	5	6
WEIGHT	.49054	-.25753	-.26251	-.29893	.31759	.65872
ROAD SPEED	.15168	.67293	-.37872	-49054	-.19883	.31744
RANGE	.14781	.66038	.49207	-.41918	.35207	-.01576
ENGINE POWER	.52002	.03143	-.41209	.04364	.32049	-.67391
ARMOUR	.50272	.00358	.13094	-.32113	-.78702	-.08706
CALIBRE	.43746	-.20914	.59880	.62392	.11714	.05776

Components with eigenvalues <1 account for less variance of the original variables (usually choice is eigenvalue> 1)

Table 4: Number of manufactured tanks by country and PC values (selected models)

Country	Tank Name	Year	Quantity	PC1	PC2
Germany	Panzerkampfwagen 3	1941	5728	.1240436	.1399211
	Panzerkampfwagen 4	1943	11900	.8720915	.2788949
	Panzerkampfwagen 5 - Panther	1942	6000	2.936454	.1894711
	Panzerkampfwagen 6 - Tiger	1942	1355	3.481624	-1.284722
	Panzerkampfwagen 6 - Tiger 2	1944	485	4.855554	-1.105824
USSR	T-34/76	1940	34000	1.805007	1.390257
	KV-1	1940	9200	2.496946	-.0170016
	KV-2	1940	330	3.964606	-1.477566
	T-60	1941	12584	-1.194056	4.279655
	T-40	1941	230	-1.676493	2.247915
	T-70	1942	8226	-.4021318	2.986667
	T-34/85	1943	18000	2.24252	1.2318
	T-44	1944	965	2.8654	.7024316
	JS-1/2	1944	7600	3.24815	-.9179595
	JS-3	1945	2311	3.475639	-.943263
UK	Cruiser Mk 5 (Covenanter)	1940	1700	-.768018	.8314859
	Cruiser Mk 6 (Crusader)	1940	5300	-.0259859	1.779674
	Valentine Tank	1940	8275	-.3075766	-1.091966
	Cruiser Mk 7 (Cavalier)	1941	500	.4600362	1.21691
	Cruiser Mk 8 (Centaur)	1941	950	.5362918	1.380761
	Churchill Tanks (A20-A22)	1941	6268	2.199254	-1.282677
	Cruiser Mk 8 (Cromwell)	1943	4200	2.487875	1.886112
	Challenger (A30)	1943	200	2.185204	.2403112
USA	M2A4 Light	1940	365	-1.116781	.0215736
	M3 Light (Stuart)	1941	13859	-.7091648	.7521166
	M3 Medium	1941	7200	.8212128	.1771654
	M5 Light (Stuart)	1942	8884	-.3718613	1.124284
	M22 Light (Locust)	1941	830	-1.193274	1.290847
	M4 Medium (Sherman)	1942	58000	1.289687	-.0015623
	M6 Heavy	1942	40	2.761417	-.5967936
	M24 Light (Chaffee)	1943	4731	-.0422105	.3376803
	M26 Medium (Pershing)	1944	1400	2.568808	-.0106361

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Figure 1: Total number of tank models present in the sample

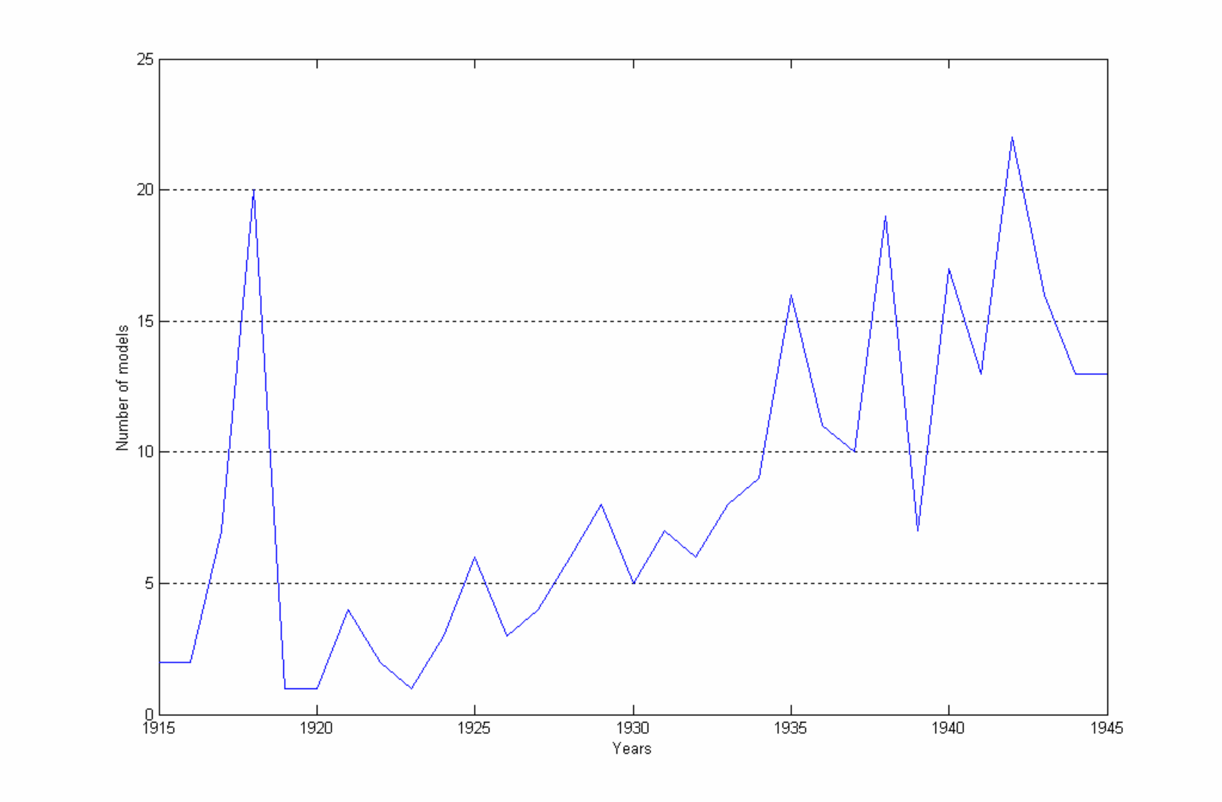


FIGURE 2A: TANK MILESTONES BY ARMAMENT CALIBRE (IN MM)

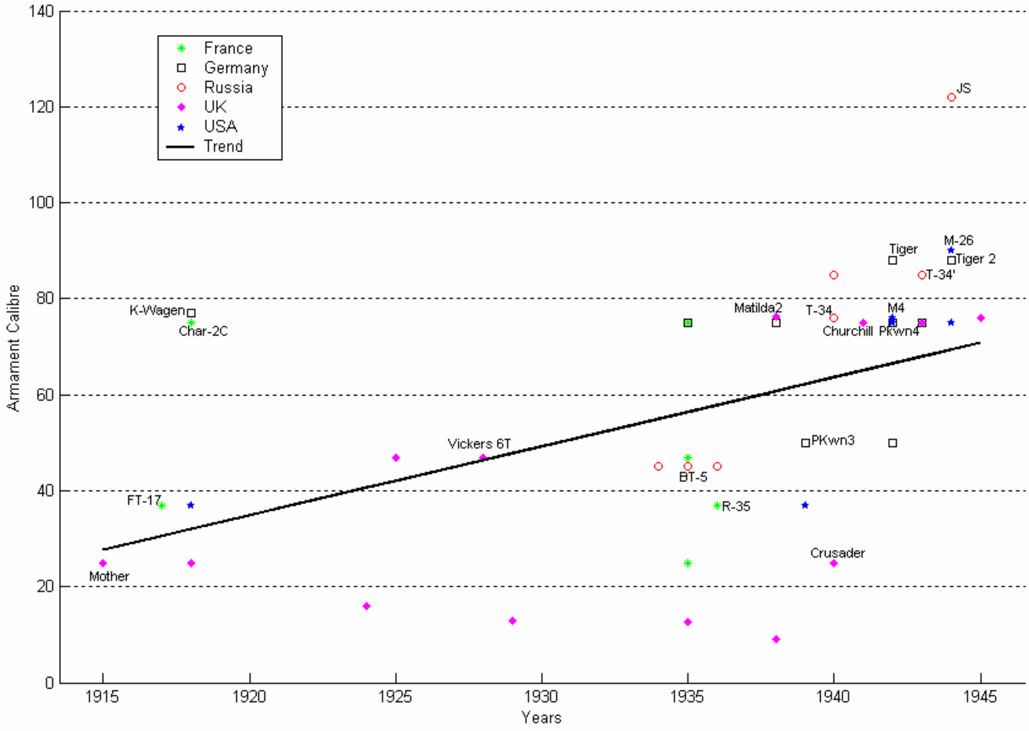


Figure 2b: Tank milestones by armour (in mm)

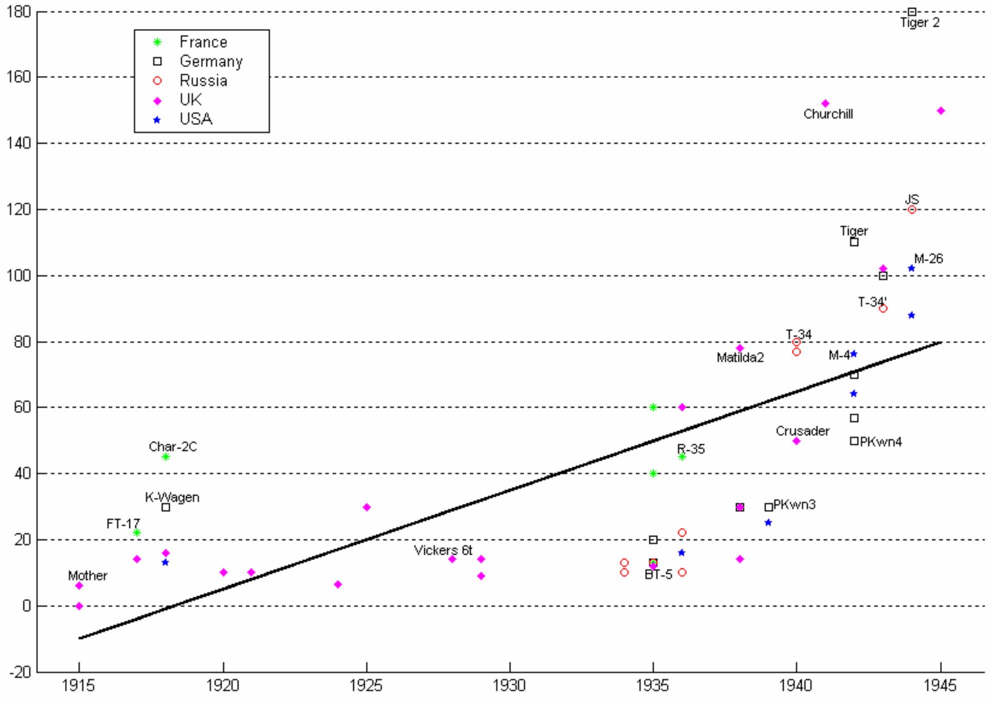


FIGURE 2C: TANK MILESTONES BY ROAD SPEED (IN KM/H)

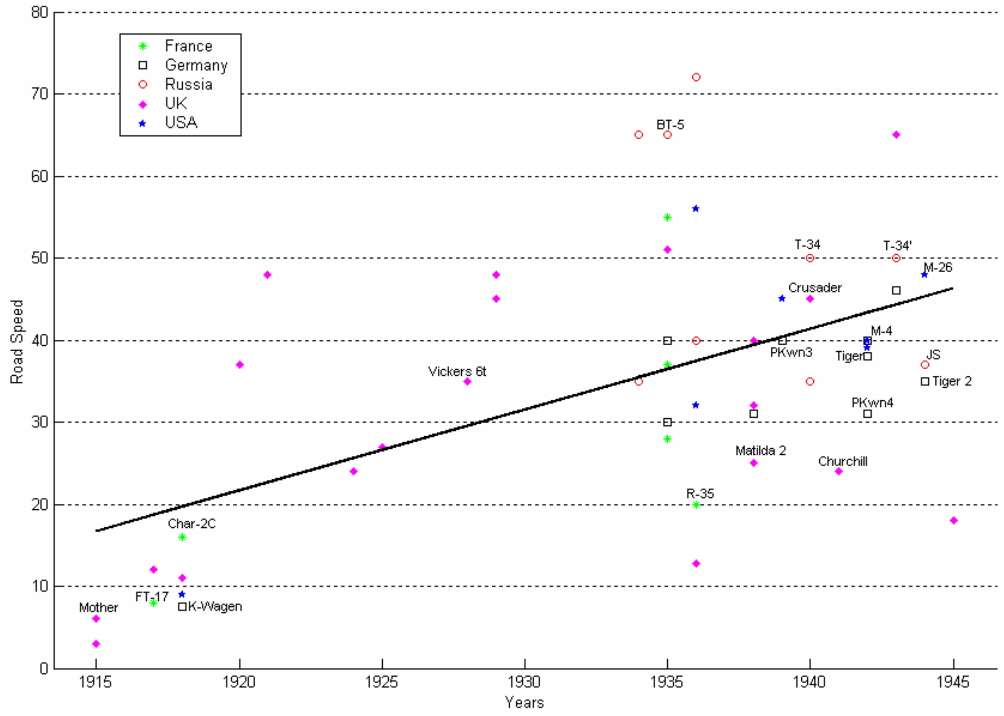


FIGURE 3: A CONCEPTUALISATION OF TANK TECHNOLOGY IN THE DESIGN AND SERVICE SPACE

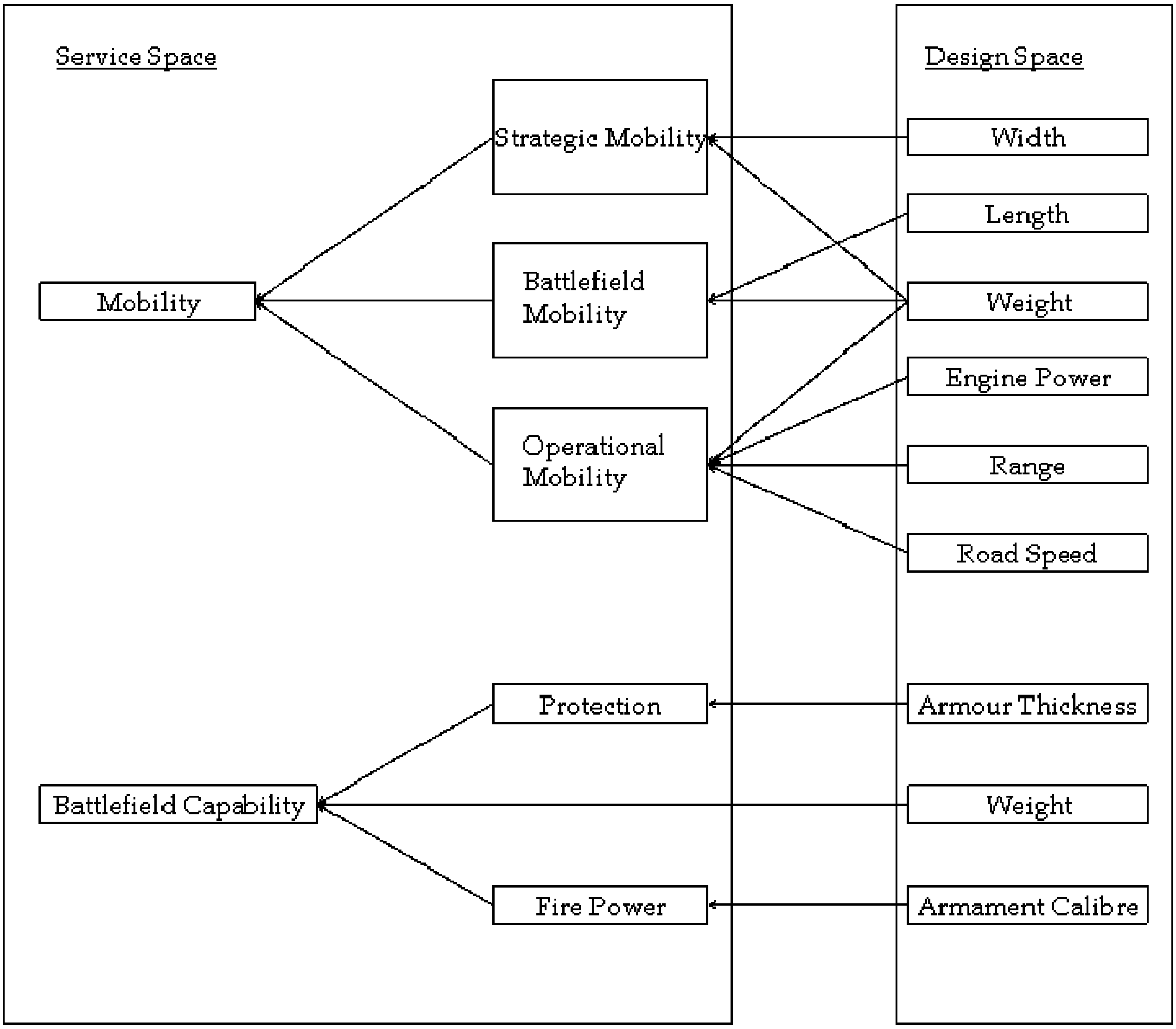


Figure 4a: Principal Components for milestone tanks (1915-1920)

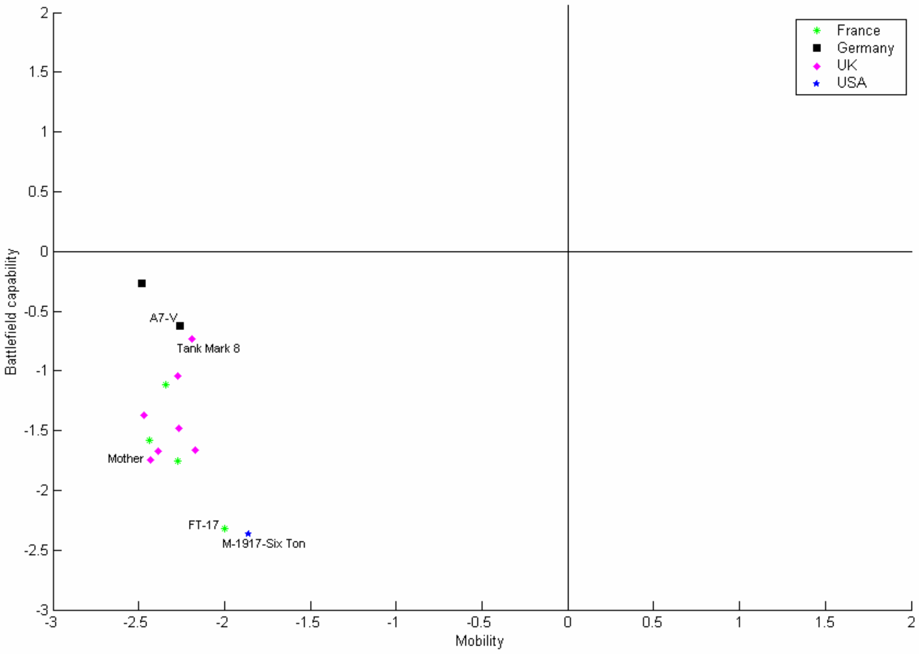


Figure 4b: Principal Components for milestone tanks (1921-1930)

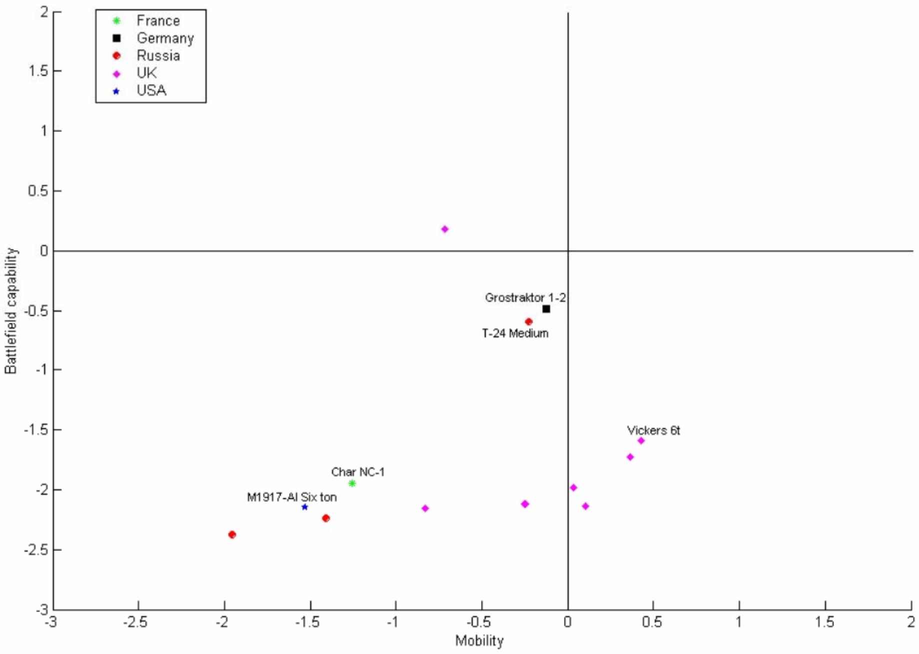


FIGURE 4C: PRINCIPAL COMPONENTS FOR MILESTONES TANKS (1931-1939)

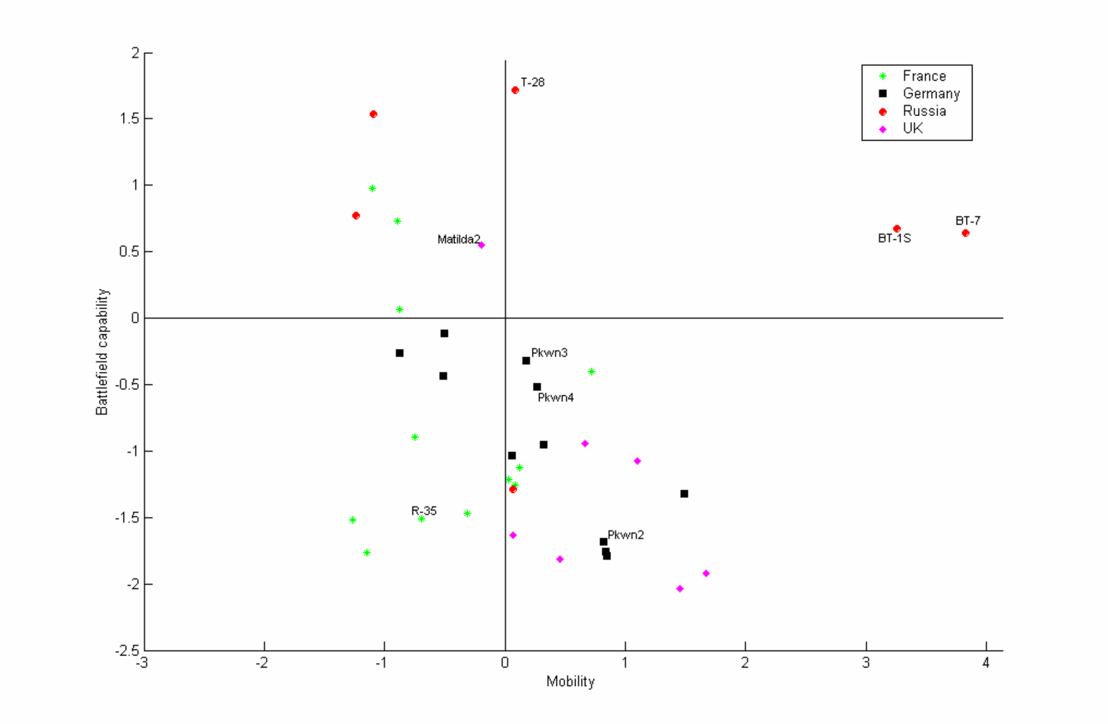


FIGURE 4D: PRINCIPAL COMPONENTS FOR MILESTONES TANKS (1940-1945)

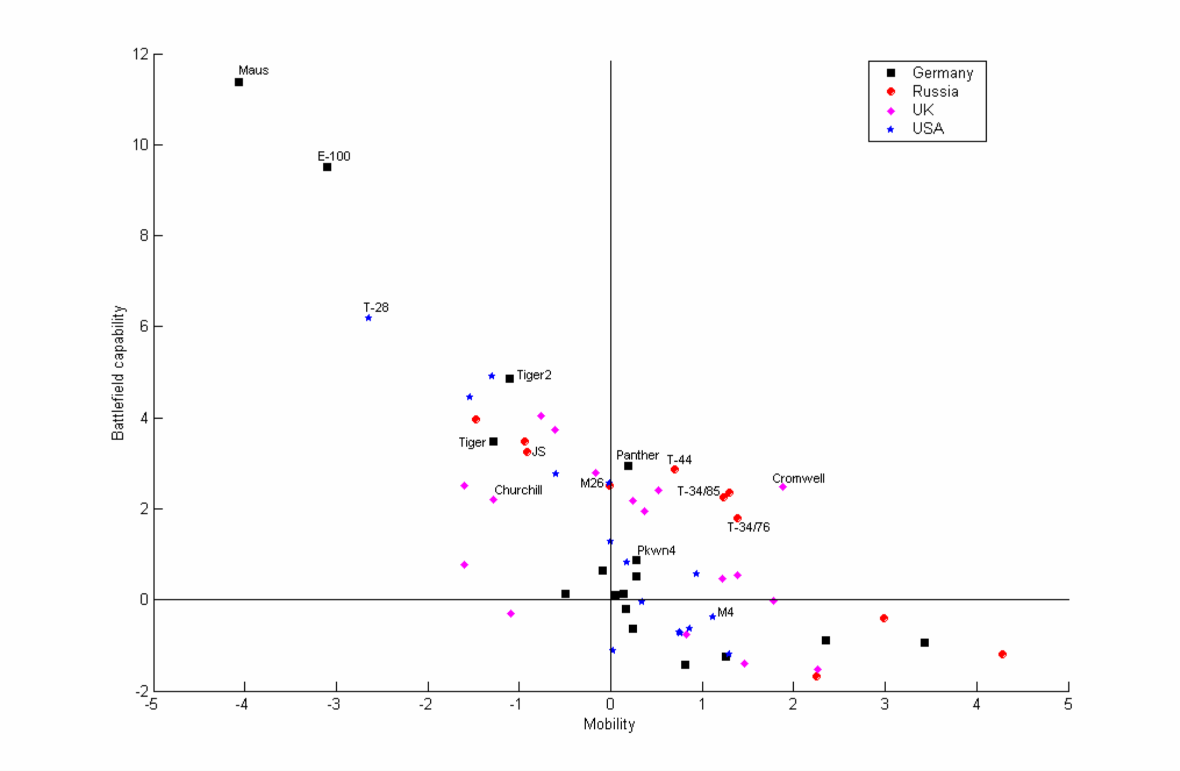
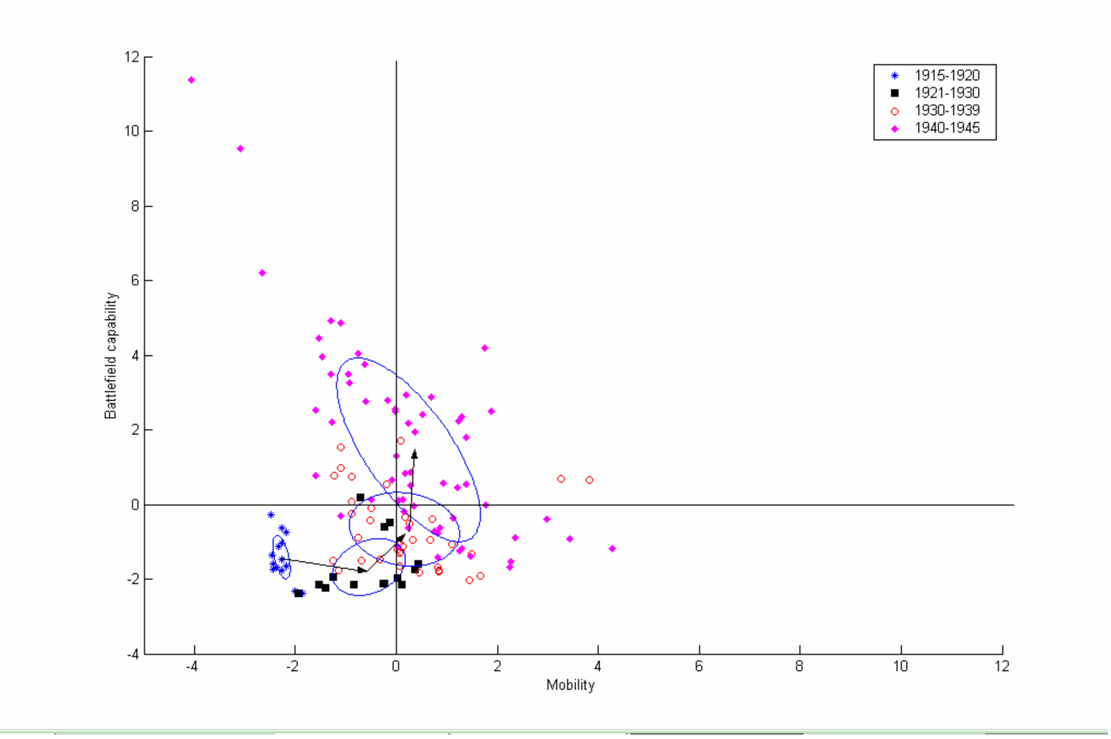


FIGURE 5: THE TRAJECTORY OF TANK TECHNOLOGY, 1915-1945.



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