Naval Engineering and the Origins of Technology-Skill Complementarity*

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Abstract

This paper revisits the debate over whether technological changes in the late nineteenth-century were skill using or skill substituting by looking at the technological developments of the United States Navy. The framework we use in analyzing the problem is Goldin and Katz (1998) who describe manufacturing as two distinct stages, a machine-installation and maintenance stage (called “capital maintenance”), and a production stage (called “production”). Skilled labor must be utilized in both stages, and technological changes can either increase or decrease the relative demand for skilled workers in each stage. To enter the debate, we exploit a unique dataset that contains the names and characteristics of every serving naval engineer from 1870 to 1899 and match merge this information with their duty and service records. We also record the names, characteristics and station of every U.S. naval vessel during this period. From this we are able to determine those engineers working in “capital maintenance” (that is, working on repairing vessels docked in navy-yards) and those working in “production” (that is, working on vessels deployed at sea). Our preliminary findings suggest that more engineers served on newer vessels, controlling for other ship characteristics. At the same time, fewer engineers were needed to repair and maintain the newer vessels. Naval technological developments thus appear to run counter to Goldin and Katz’s findings - in this industry. Maintenance and repair became skill-saving while production became skill-using.

- *Keywords*: skilled-labor complementarity, skill-replacing technology, skill-using technology
- *JEL Codes*: J24, N31, N71, O30

1 Introduction

This paper revisits the debate over whether technological changes in the late nineteenth-century were skill using or skill substituting by looking at the technological developments of the United States Navy. Goldin and Katz (1998) demonstrate that capital-skill complementarities were apparent in the U.S. economy as far back as the beginning of the twentieth century. Earlier periods however remain mysterious to us; here we look to the relations between workers and vintage capital in the U.S. Navy to observe the inter-relationships between factors and technologies in a particular industry.

We view the vessel as a floating firm, an island of productivity in which technology-embodied capital is employed by various types of skilled and unskilled labor in pursuit of the objectives of the voyage. The specific objectives, be they to blockade trade, or to engage in gunboat diplomacy, or to provide a vague appearance of power projection, are for the most part opaque to us. But as the United States during the latter 19th century transitioned from its traditional limited strategy of commerce raiding and shore protection (guerre de course) to a far more muscular naval strategy (guerre d'escadre), these endeavors grew increasingly vital to the health of U.S. commerce and security.[1] In this sense the Navy was a critical "industry" in the overall economy, one from which we can learn a great deal.[2]

The framework we use in analyzing naval activities is similar to Goldin and Katz (1998) who describe manufacturing as entailing two distinct and sequential stages, a machine-installation and maintenance stage, and a production stage. There are two kinds of skilled workers: officers (who act as managers) and engineers (who act as technocrats); these skilled laborers work with technology-embodied capital (the naval vessel) and unskilled labor (the vessel's complement). They can work either in the production or repair of naval vessels (what we will call "maintenance"), or in the operation of vessels in international waters (what we will call "production"). With this framework, we attempt to observe the extent of each skilled labor-type's complementarity with capital, raw labor, evolving naval technology, and each other. What we find should not be too far off from the productive relations between inputs in other highly complex industries. We also wish to observe these relationships during the maintenance or implementation of capital portion separately from the actual production portion. Again, the insights we gleam can

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[1] Examples abound where the Navy was used as a tool of macroeconomic policy. For example, the United States' "gunboat diplomacy" in Venezuela, which began in the mid-1890s, was motivated in part by concerns over debt repayment (Reinhart and Rogoff 2009).

[2] Some words of caution come from a military historian - "The past - even if we could be confident of interpreting it with high accuracy - rarely offers direct lessons" (Paret 1986). Indeed, but the dynamics of technological change within the naval steamship can surely provide *indirect* evidence of the nature of industrialization for the other complex industries of the day.

help us better understand the multi-stage production processes in 19th century industry.

Our analysis finds a number of things. For engineers, there are very clear capital-skill and technology-skill complementarities (where technology is proxied by the age or the speed of the vessel). For officers, these complementarities are noticeably weaker; however there are very strong officer-unskilled labor complementarities. These results highlight the need to distinguish the type of human capital being scrutinized - it is conceivable that management-type skills would work closely with personnel, whereas engineer-type skills would work less with people and more with machinery and technical apparatus. We also find that these technology-skill complementarities disappear for the maintenance portion of production; if anything newer and/or faster vessels require fewer engineers to repair. This result suggests that naval production does not fit the Goldin and Katz framework, whereby skilled-labor is increasingly needed in machine-installation and maintenance activities. In this industry, production itself was a very complex endeavor requiring more and more technocrats to properly execute. Perhaps other industries of the 19th industry behaved similarly, or perhaps instead the Navy was a portent of the way industry would operate in the 20th century.

The rest of the paper is organized as follows. Section 2 provides some background and motivation. Section 3 frames our concept of naval activities, while section 4 describes how we empirically test this framework with the data we have. Section 5 briefly describes the data; section 6 then details our results.

2 Background

2.1 Naval technological evolution

The late 19th century Navy employed a heterogenous fleet of vessels which were built between the 1850s and 1890s. All were steamships, but they had radically different technological designs which were highly dependent on the years of their conceptions. This was a transformative era for both the Navy and the greater economy; studying this era thus gives us a unique opportunity to examine the use of capital, each embodied with different types of technologies.

Nearly every facet of the naval ship was transformed during the late 19th century. These changes included the switch from sail to steam propulsion, the ironcladding of wooden hulls, the full construction of iron hulls, the switch from paddle-wheels to propellers, and the implementation of rifled barrels and exploding projectiles in naval ordnance. Indeed, "by century's end, warships were complex systems that bore little resemblance to those fifty years earlier"(McBride 2000).

Yet because of delays in technological adoption during the 1870s and 80s, the Navy also employed many ships of antiquated design and ability. The conversion of the fast cruising *Madawaska* to the steam frigate *Tennessee* during the early 1870s is a classic example. Like many vessel conversions during this time, the *Tennessee* essentially became a "totem of romantic tradition," complete with white oak hull and all of the traditional ship fittings of the old sailing navy (Vlahos 1989). These ships were designed not so much to fight as to merely give the impression of being able to fight. Ship designers were in fact directed to embrace naval anachronisms. A general order in 1869 for example directed that"hereafter all vessels of the navy will be fitted with full sail power...Commanders of squadrons will direct that constant exercises shall take place with sails and spars" (Bennett 1896).

Some of this was due to American postbellum withdrawal from the international scene, and a renewed focus on southern reconstruction and westward expansion. But such reactionary designs were common even before the war - in 1857 for example, instead of experimenting with large steamships with screw propulsion designs and armored hulls in emulation of the British, Congress approved the construction of five large but wooden hulled, shallow-draft sloops (Tomblin 1988). Battles over ship designs between line officers and naval engineers which began in the 1850s fostered a kind of technological stasis up through the 1870s - the Navy settled on romantic ship configurations rather than make a bold change to the battleship paradigm (McBride 2000).

But change did come. During the 1880s there were two distinct waves of technological catch-up - the construction of the armored ABCD ships, and the four modern heavy cruisers *Texas*, *Maine*, *New York*, and *Olympia*. The navy began its attempts to converge to the technological frontier in earnest; for example American officers made technical pilgrimages to Europe in 1886, paying $2500 to purchase foreign designs of naval warships (Vlahos 1989).

After this an even greater push for modernization was made by Secretary of the Navy Benjamin Tracy, who established the Board of Construction in 1889 to coordinate the bureaus' efforts to produce optimal warship designs themselves (McBride 2000). The vessels subsequently designed and launched were radically different in both design and ability. In fact to some, "the new navy is one so different from much that has preceded...as to make it a subject by itself, only slightly connected with all that has gone before" (Bennett 1896). Yet from the end of the war to the beginnings of this "new navy," some forty new war steamers had been added to the Fleet (Vlahos 1989). The 19th century U.S. Navy was thus made up of a mongrel mix of old and new ships, providing us a rich environment to explore the effects of such technological diversity on the mix of labor-types needed for naval operations.

2.2 Was naval capital and technological growth "skill-biased?"

We argue that this industry and period merits close empirical scrutiny, for the answer to this question does not immediately surface from the historiography alone. Since the steam engine is "still widely regarded as the quintessential invention of the Industrial Revolution" (Mokyr 1990), the answer should be of great interest to both economic and naval historians. The answer is also a difficult one - even contemporaries often failed to get a true sense of how capital and technology complemented skilled personnel: one officer described the difficulties the navy had in progressing technologically as arising from the failure of "officers in high position to realize the duality of the naval profession; to realize that a navy consists of both personnel and material; the two of equal importance, and each useless without the other" (McBride 1992).

On the one hand, it seems logical to suggest that implementation of steam technologies would require more engineers to handle and exploit such technologies. Along with propulsion, vessels began to develop steam engineering techniques to clear bilges of water. Further, as vessels began to increase in size, steering by manual labor became increasingly onerous and new steam techniques to steer ships were developed and implemented (Smith 1937). This would seem a clear example where larger and newer ships would require more engineer personnel. Yet even these sorts of technologies could be viewed as engineer *replacing* - the engineer who designed the first successful steam steering engine in 1866 states that one condition for its use was for "the apparatus to be simple in all its parts and requiring no special attendant or engineer" (Smith 1937).

The increase in the size of naval guns also led to the introduction of machinery for controlling them. As early as 1861 there existed a system of mounting heavy guns on a turntable, the revolution, gun motion and recoil all powered by steam. Such turrets worked by steam became standard in newer vessels. Clearly these replaced wooden carriages and manual labor, but whether more engineers were needed, or simply more officers specially trained in modern ordnance, remains unclear.

These are but a few examples of how technical changes could alter the optimal mix of skilled labor aboard vessels. Steam was applied to pumping, steering, the working of guns, the distilling of water, and the charging of torpedoes, along with its traditional role in propulsion. Yet none of these functions makes the need for more engineer specialists manifestly apparent. In general, adoption of simple steam technologies could require *fewer* engineers on hand. After all, Watt's original invention was designed to be implemented simply, cut costs, minimize wear and tear, and "extract the last drop of duty from the last puff of steam [from the] engine" (Mokyr 1990). Other histories of naval steam engineering seem to echo this economization of engineer expertise. For example according to one article from the late-19th century, a steam frigate of 1000 horsepower in 1865 required nine engineers; in 1896 an armored steam cruiser of 17,000 horsepower required only five.[3] One might consider this engineer-replacing since there are fewer aboard the newer ship; at the same time there is far more horsepower generated per engineer for the newer ship, reflecting huge technological progress. We wish to inquire whether or not this example is emblematic of the replacement of engineers on technologically advanced vessels, or rather an interesting exception to the general rule.

Another consideration is the degree of complementarity between naval officers and engineers. If these workers were highly substitutable, advances in naval capital and technologies could further push out engineers by replacing them with (conceivably lesser paid) officers. This could have created a further impetus for engineers to leave naval service, as developments in private industry dramatically raised the rewards in engineer-oriented professions (Glaser and Rahman 2010).[4]

Again, we need to look to the data to discover any systematic substitution. The history would seem to suggest that during this period offices and engineers had radically different functions. Just how mysterious the workings of steam technologies were to line officers is summed up rather trenchantly by Commander R. S. Robinson of the Royal Navy back in 1839: "we go into the engine room, we look at the outside of an engine, various rods of highly polished iron are moving about, a beam is observed vibrating up and down, all is clean and bright and well arranged, but the working parts of the engine, the moving power is entirely shut out from our sight, and after staying a few minutes and, perhaps, asking a question or two, which from the very depths of ignorance it betrays, it is scarcely possible the engineer can or will answer, we walk up again, with no additions to our knowledge, and rather convinced that the whole subject is incomprehensible" (Smith 1937).

The period that we study is one where the corps of naval personnel was "pre-amalgamated" - that is, officers and engineers had explicitly separate duties. The engineers allegedly served as an indispensable corps with extensive scientific and technical expertise, the "inspectors and constructors of machinery," and those also with "practical ability if the ship's machinery were to be kept in an efficient condition" (Bennett 1896). Officers by contrast specialized in seamanship, navigation, weaponry and general strategy. This separation persisted up until the Amalgamation Act of 1899 - through this period the fear of "the sailor swallowing the engineer, or the engineer swallowing the sailor" had not come to pass (Bennett 1896). Thus in evaluating potential complementarities, we need to look at both types of skilled labor separately for both the maintenance and the usage of vessels.[5]

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[3] from "Queer Doings in the Navy," *Scientific Machinist*, July 1, 1896.

[4] Evidence of the explosive growth in engineer employment in manufacturing abounds. In 1880 there were 7061 engineers in the U.S.; at the turn of the century there were 43,239 (Blank and Stigler 1957).

[5] Edelstein (2001) stresses how proper complementarity measurements between different laborer-types is important for growth accounting, citing Field-Hendrey (1988, 1998) who demonstrate the lack of substitutability

3 Conceptual Framework

The conceptual framework we use comes from a generalization of the approach in Goldin and Katz (1998).[6] There they treat manufacturing as a process with two distinct sequential stages, a machine-installation and maintenance stage, and a production and assembly stage. The workable capital produced in the first stage is then employed in the second to produce final output. This approach seems particulary apt for naval productive activity, since much maintenance work must be performed on vessels before they can become operational and set out to sea. However, their framework presupposes that the first stage is highly education-intensive, while the second is unskilled labor-intensive. The extent to which naval production exhibited both capital-skill and technology-skill complementarities in *either* stage is our primary focus. Thus we will need to envision a more general framework.

Specifically, consider the capital production/maintenance stage as one that produces usable (a.k.a. sea worthy) vessels, denoted by K^*. Production of K^* is given by

$$K^* = \left[\beta\left(K\right)^{\theta} + \left(1-\beta\right)H_K^{\theta}\right]^{\frac{1}{\theta}} \tag{1}$$

where K is the capital of ships under repair, and H_K is the skilled workforce assigned to repair these ships.[7] This skilled workforce is composed of both naval officers and naval engineers - how they work together in ship production and maintenance can be generally described as

$$H_K = \left[A_{O_m}O_m^{\sigma} + A_{E_m}E_m^{\sigma}\right]^{\frac{1}{\sigma}} \tag{2}$$

Here O_m and E_m denote the officers and engineers working in maintenance, while A_{O_m} and A_{E_m} denote each group's level of productivity.

Once vessels become sea-worthy, they can be used for naval voyages. We can thus consider naval "production" (Q) as some measure of sea power projection, or degree of naval exposure in international waters. This production can be quantified as

$$Q = A_Q\left[\alpha\left(K^*\right)^{\rho} + \left(1-\alpha\right)H_Q^{\rho}\right]^{\frac{1}{\rho}} \tag{3}$$

where H_Q is the skilled workforce assigned to vessels out at sea. Similar to H_M, this workforce is comprised of officers and engineers, and the aggregation between the two can be described by

$$H_Q = \left[A_{O_q}O_q^{\varepsilon} + A_{E_q}E_q^{\varepsilon}\right]^{\frac{1}{\varepsilon}} \tag{4}$$

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between labor of different servitude-status or gender.

[6] For alternative two-stage approaches see Papageorgiou and Saam (2008) for a CES-production example, or Chin et al. (2006) for a maritime example.

[7] We ignore unskilled labor here for the sake of exposition and brevity.

where O_q and E_q are the officers and engineers engaged in naval voyages, and each has their own level of productivity.

The parameters $\theta \leq 1$ and $\rho \leq 1$ determine the elasticities of substitution between capital and skilled labor in ship maintenance and ship use, respectively. The parameters $\sigma \leq 1$ and $\varepsilon \leq 1$ determine the elasticities of substitution between engineers and officers in ship maintenance and ship use, respectively. These, along with the labor-specific productivity parameters, determine the extent to which there exists capital-skill and technology-skill complementarities in naval production. Further, all these have the potential to change over time, affecting the optimal mix of engineers and officers working in maintenance and on sea-faring vessels.

Note that our empirical exercises will not allow us to quantitatively isolate each parameter, or the changes in each parameter over time. For example, assume that $\varepsilon < 0$ (so that we might consider officers and engineers working abroad sea-going vessels as grossly complementary). If we observe a rise in engineers aboard active vessels over time, we might attribute this to a rise A_{O_q}, or to a fall in ε, or to both - without further structural restrictions we cannot tell from the data. The above suggests that potential complementarities in maintenance and production can arise from a variety of sources. The empirics that we present below attempt to document these complementarities without pinpointing the precise source for them.[8]

4 Empirical Framework

For this stage we only seek to estimate relationships in the conceptual framework outlined in section 3 with simple reduced form specifications. We regress 3 alternative measures of skilled labor (engineer) intensity on a variety of ship and shipyard characteristics.

For the first set of estimates, define y_i as a non-negative count variable with integer values $0, 1, 2, ...$ Specifically this represents the total number of engineers assigned to ships and shipyards indexed by i during year t. Poisson regression is a natural empirical specification for the analysis of count data such as this. An examination of the distribution of engineers and officers shown in figure 2 provides additional further motivation for the assumption of a poisson model. Following from Wooldridge (2002), we estimate the conditional mean given the vector x_i such that $E(y_i|x_i) = \mu(x_{it})$. The Poisson defined conditional distribution is given as

$$f(y|x_i) \ = \ \frac{exp\left[-\mu(x_i)\right] \ \mu(x_i)^y}{y!} \ , \qquad y = 0, 1, 2, ... \ , \tag{5}$$

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[8] We could consider a dynamic program where the Navy maximizes a temporal stream of Qs by choosing O_q and E_q each period, taking technologies, elasticities of substitution, K, $O = O_q + O_m$ and $E = E_q + E_m$ each period as given. Of course, the dynamic naval program would be a lot more complicated than that, since the Navy must match particular types of K^* with particular Os and Es. The simple static structure outlined above however suffices in framing our empirical exercises and results.

where $\mu(x) = exp(x\theta)$. Our interest is in the $K \times 1$ vector of parameters in θ. For discussion and comparison, we also include estimates of random effects Poisson regressions. Our estimates of (5) appear in tables $2, 3, 4$ and 7.

We also exploit the panel structure of our data to evaluate how changes in the capital and technological characteristics of ships and shipyards leads to changes in the structure of officer corps on ships and serving in shipyards. Which attributes lead stations to rely on more experienced (and possibly less technically savvy) engineers? What caused the share of engineers relative to line officers in various stations change over time. In both cases, we seek to uncover the set of factors that leads to changes in the skill intensity of officers on ships and in shipyards.

The basic unobserved effects model estimates engineer intensity over time assuming the specification

$$y_{it} = x_{it}\beta + c_i + u_{it} , \qquad t = 1, 2, ..., T . \tag{6}$$

The random variable c_i controls for unobserved heterogeneity and improves consistency of estimates in the $K \times 1$ vector β. By empirical construction, our estimates assume that c_i is not correlated with x_{it}. Results from FGLS estimation of engineer intensity on ships using (6) appear in tables 5 and 6.

5 Data

Our core empirical strategy regresses skilled personnel intensity on a variety of ship characteristics. In order to do this of course we need to match officers and engineers to particular vessels. We accomplish this by exploiting information compiled in the Navy Registers. These are annual volumes published by the Navy documenting the duty and station of every serving officer and every naval vessel. From these volumes we determine the numbers of officers and engineers assigned to each vessel each year, as well as the station of each vessel. There are typically core groups of each skilled labor-type during each ship's international tour, but nevertheless a remarkable degree of year-to-year fluctuation in personnel exists even during the same tours.[9] Thus we exploit the panel nature of our data and use observations at the ship-year level.

What about those vessels under repair? Typically these vessels do not have specific personnel listed (as the ship is dry-docked, there is no active roster assigned to the ship). They are, however, docked in specific and identifiable navy-yards, so we can match skilled naval personnel assigned to specific navy yards with the repair of vessels docked in those same yards. We also construct

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[9] For example, a vessel could be stationed in the pacific for five years while the numbers of officers and engineers aboard the vessel vary year to year as the ship docks at certain ports and personnel exit the enter at various times.

aggregate measures of ship characteristics under repair in these yards during particular years. This helps us build a longitudinal dataset, where time is measured at the yard-year level.

We match the primary data extracted from the Navy Registers with two other sources. The first is the appendix of Bennett (1896), which lists every serving naval engineer up until 1896. This is used to construct some basic experience measures for each engineer. This work also includes a list of vessels and basic ship attributes such as displacement, ship dimension, and year of build. The second source is the Dictionary of Fighting Ships, which is used to augment ship information in Bennett (1896). This also allows us to include newer vessels and other vessel traits such as the complement (the number of sailors and other crew members) and ship cruising speeds.

Our final match-merged data includes the personnel and status of every active and repairing U.S. naval vessel from 1870 to 1899. This span of time gives us a wide range of steam vessel-types that are both active and repairing, so that we can track the factors linked to very different technologically-embodied ships; technological proxies include the age of the vessel and its speed (the age profiles of all active and repairing vessels are illustrated in figure 1). At the same time, our period deals strictly in the pre-amalgamation age, so that we analyze two distinct skill-types, each with very distinct functions and responsibilities.

Finally, we include year effects for all pooled poisson regressions. For specifications that control for unobserved heterogeneity, we include time-specific controls for each decade. These conceivably important controls reduce bias from the omission of time-specific factors such as changes to naval budgets, variations in aggregate naval personnel, and shifts in international relations.

Table 1: Descriptive statistics of ships (conditional on active service)

ship characteristics	observations	mean	standard deviation	minimum	maximum
engineers (at initial observation)	127	3.19	1.93	0	9
average engineer experience (initially)	118	12.74	5.00	2.17	27.79
officers (initially)	127	7.69	3.00	0	16
percentage engineers	127	0.293	0.168	0	1
age (initially)	127	12.4	6.9	3	32
max speed (knots)	105	12.6	3.7	5.5	23
displacement (tons)	124	2721.9	2182.7	420	11296
length (feet)	126	241.7	58.2	16	411
complement (sailors)	89	241.7	146.6	12	727

6 Results

6.1 Production - vessels out to sea

Our first empirical exercise regresses the concentrations of engineer personnel or line officers aboard active vessels on vessel characteristics including variables controlling for size, speed, age, complement and various proxies of a vessel's wear and tear. For these we use Poisson pooled and Poisson random effects regressions, since dependent variables are count variables with nearly equal mean and variance. The count profiles of both engineers and officers aboard active vessels are illustrated in figure 2, while descriptive statistics appear for variables included in regressions appear in table 1. Many ship-characteristic variables are not time dependent - these include measures of displacement (in tons), length (in feet) and complement (the total number of ship personnel as recorded in the *Dictionary of Fighting Ships*). Variables that evolve over time include the age of the vessel, the cumulative number of years since 1870 that the ship has been active at sea ("cumulative sea"), the cumulative number of years since 1870 that the ship has been in repair ("cumulative repair"), and the number of naval officers assigned to the vessel.

6.1.1 Engineer counts

Tables 2 and 3 present results for engineer counts serving on active ships at sea, the estimates of which derive from methodology outlined by (5). In pooled regressions, estimates support basic hypotheses for the presence of technology-skill and capital-skill complementarities in naval activity. The age of the active vessel negatively relates to the number of engineers assigned to the ship, while the vessel's displacement and length positively affect a vessel's roll of engineers. Changes on the margin are small, but the results clearly indicate that larger, longer and newer ships received more engineers, i.e. the more technically inclined.

Notably the complement of ships (i.e. number of sailors) did not affect engineer counts. Ships that received numerous repairs prior to voyage (cumulative repair) consistently required more engineers once underway at sea, perhaps an indication of vessels prone to frequent servicing even at sea. We also observe a strong inter-skill complementarity - the number of officers aboard the vessel raises the number of engineers. Each additional officer approximately increases engineers by 0.16. While the result is robust across specifications, it is also likely endogenous[10]. Without

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[10] To "test" for the sensitivity of officer coefficients to endogeneity, we implement an initial two-step correction method, using "complement" as an instrument. Note from table 4 how "complement" demonstrates a positive relationship with officer rolls, but tables 2 and 3 indicate that "complement" is not correlated with engineer rolls on ships.) Our initial endogeneity "corrected" specification (not shown) indicates an officer coefficient of 0.08 with a marginal effect of 0.24. This indicates a *ceteris paribus* 4 to 1 ratio of officers to engineers rather than the 2 to 1 ratio indicated by simple unconditional statistics.

further estimates and robustness checks, however, we do not discuss this further in this draft.

Table 2: Poisson regressions of number of engineers assigned to active vessels on vessel characteristics

VARIABLES	1	2	3	4	5	6	7
age of vessel	-0.01***	-0.015***	-0.018***	-0.015***	-0.011*	-0.019***	-0.014
	(0.002)	(0.003)	(0.003)	(0.003)	(0.007)	(0.003)	(0.009)
	[-0.038]	[-0.050]	[-0.048]	[-0.043]		[-0.054]	
displacement (tons)	0.0001***	0.00008***	0.0001***	0.00008***	0.00005*	0.00008***	0.00004
	(0.00001)	(0.00002)	(0.00001)	(0.00001)	(0.00003)	(0.00002)	(0.00003)
	[0.0002]	[0.0002]	[0.0002]	[0.0002]		[0.0002]	
length (feet)	0.003***	0.003***	0.003***	0.003***	0.002*	0.003***	0.0008
	(0.0004)	(0.0008)	(0.0004)	(0.0004)	(0.001)	(0.0007)	0.001)
	[0.009]	[0.007]	[0.010]	[0.008]		[0.008]	
complement (sailors)	–	0.0005	–	–	–	0.0002	0.0006)
		(0.0003)				(0.0003)	(0.0007)
		[0.002]				[0.0007]	
cumulative sea	–	–	0.01*	0.008	0.018	0.01*	0.016
			(0.006)	(0.006)	(0.014)	(0.006)	(0.014)
			[0.020]	[0.022]		[0.023]	
cumulative repair	–	–	0.014***	0.018***	0.025*	0.02***	0.03**
			(0.006)	(0.006)	(0.014)	(0.007)	(0.013)
			[0.042]	[0.052]		[0.051]	
officers	–	–	–	0.056***	0.070***	0.04***	0.06***
				(0.009)	(0.012)	(0.01)	(0.014)
				[0.164]		[0.158]	
observations	798	563	798	798	798	563	563
number of vessels	124	87	124	124	124	87	87
pseudo R^2	0.15	0.15	0.15	0.16	–	0.14	–
goodness of fit $\bar{\chi}^2$	495.7	337.5	489.8	465.4	–	323.8	–
year effects	yes	yes	yes	yes	no	yes	no
random ship effects	no	no	no	no	yes	no	yes
LR test of random effects	–	–	–	–	26.69***	–	13.63***

*** p<0.01, ** p<0.05, * p<0.1

bootstrap coefficient standard errors shown in parentheses

marginal effects (dy/dx) shown in brackets

One might consider the use of vessel age as a proxy for technology. This is defensible on the basis of the historiography of the navy - technological progress happened in fits and starts, but it also happened *chronologically.* Thus the year of a ship's construction gives us a fair sense of the technological vintage of the vessel. Still, a more overt measure of the technical capability of a vessel might be its potential cruising speed, for this was one of the main goals of improving steaming techniques. We have this information for only 80% of our sample of vessels, leaving a sizeable chunk of missing information in our data. To empirically address this and test for sensitivity of results in table 2.

The alternative results of these estimations, presented in table 3, provide a somewhat more clear indication of the complementarity between technology and engineering-skill on active vessels. Even controlling for the age of the ship, an extra knot of speed is associated with marginal increase of 0.07 engineering personnel. Moreover and after controlling for the speed (i.e. technology) of the vessel, a decline in engineering personnel persists for every year the ship ages. Again, we observe robust positive effects on engineer numbers from the size of ships, the number of officers and the number of years that ships have received repairs. Similarly to the results in table 2, no discernible relationship exists between the number of engineers and the ship's overall complement.

One consequence of pooling is that the disturbances may be correlated within groups, leading to serial correlation and less efficient estimates. One can think of the naive pooled regression as having a disturbance term divided conceptually into two parts, a random component, u_{it} and a group share c_i. The estimates should be more efficient than pooled regression, but still may run the risk of omitted variable bias.

Indeed, our results indicate a strong presence of unobserved heterogeneity with likelihood ratio tests for random effects all appearing statistically significant. Many coefficient estimates are sensitive to specifications that include random unobserved heterogeneity. This has important empirical implications for us and indicates a need to delve further into other sources of data for variation in the missions of ships and the technological demands of various missions, the inclusion of which could reduce omitted variable bias. For instance, speedier, larger and newer vessels embodied newer technology, which may have needed more technically savvy engineers; these same ships may have also been called into action more frequently. The distribution of a vessel "duties" at sea may have required varying demands on the types of and number of engineer personnel.

Table 3: Poisson regressions of number of engineers assigned to active vessels on vessel characteristics

VARIABLES	1	2	3	4	5	6	7
speed of vessel (knots)	0.019**	0.023***	0.025***	0.018	0.002	0.026**	-0.011
	(0.008)	(0.012)	(0.009)	(0.009)	(0.011)	(0.011)	(0.028)
	[0.054]	[0.067]	[0.072]	[0.052]		[0.075]	
age of vessel	-0.011***	-0.017***	-0.014***	-0.013***	-0.010	-0.019***	-0.017
	(0.003)	(0.004)	(0.004)	(0.003)	(0.006)	(0.005)	(0.011)
	[-0.032]	[-0.049]	[-0.041]	[-0.037]		[-0.056]	
displacement (tons)	0.0001***	0.00005***	0.00006***	0.0007***	0.00005	0.00006**	0.00002
	(0.00001)	(0.00002)	(0.00001)	(0.00002)	(0.00003)	(0.00002)	(0.00004)
	[0.0002]	[0.0002]	[0.0001]	[0.0001]		[0.0002]	
length (feet)	0.003***	0.002*	0.003***	0.003***	0.002	0.002**	0.002
	(0.0005)	(0.001)	(0.0005)	(0.0005)	(0.001)	(0.001)	(0.002)
	[0.008]	[0.006]	[0.009]	[0.008]		[0.006]	
complement (sailors)	–	0.0004	–	–	–	0.0002	0.0008
		(0.0003)				(0.0002)	(0.0008)
		[0.002]				[0.0007]	
cumulative sea	–	–	0.006	0.008***	0.017	0.008	0.015
			(0.006)	(0.007)	(0.013)	(0.008)	(0.016)
			[0.016]	[0.012]		[0.024]	
cumulative repair	–	–	0.014**	0.025**	0.022**	0.019**	0.027
			(0.007)	(0.007)	(0.011)	(0.009)	(0.018)
			[0.042]	[0.048]		[0.054]	
officers	–	–	–	0.041***	0.064***	0.047***	0.057***
				(0.008)	(0.011)	(0.012)	(0.016)
				[0.149]		[0.137]	
observations	676	515	676	676	676	515	515
number of vessels	103	80	103	103	103	80	
pseudo R^2	0.15	0.15	0.15	0.16	–	0.15	–
goodness of fit $\bar{\chi}^2$	399.6	305.6	393.0	377.9	-	294.2	–
year effects	yes	yes	yes	yes	no	yes	no
random ship effects	no	no	no	no	yes	no	yes
LR test of random effects	-	-	-	-	16.77***	-	9.95***

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

bootstrap coefficient standard errors shown in parentheses

marginal effects (dy/dx) shown in brackets

6.1.2 Officer counts

Conceivably the kinds of skills officers provide aboard a ship would be different from those of engineers, particulary prior to the Amalgamation Act after which all line officers were also required to be competent in engineering. To test for these differences, we estimate poisson specifications with the number of officers on active vessels as the dependent variable. The results from these specifications follow in table 4.

Table 4: Poisson regressions of number of officers assigned to active vessels on vessel characteristics

VARIABLES	1	2	3	4	5	6
age of vessel	-0.002*	-0.004***	-0.006***	-0.004**	-0.004	-0.006***
	(0.0013)	(0.001)	(0.002)	(0.002)	(0.004)	(0.002)
displacement (tons)	0.00005***	-0.000009	0.00006***	0.00004***	0.00002	-0.00002
	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00003)	(0.00002)
length (feet)	0.001***	-0.00002	0.0014***	0.001***	0.001	-0.0002
	(0.0003)	(0.0004)	(0.0003)	(0.003)	(0.0009)	(0.0004)
complement (sailors)	–	0.001***	–	–	–	0.001***
		(0.0001)				(0.0001)
cumulative sea	–	–	0.01***	0.009***	0.008	0.009***
			(0.003)	(0.003)	(0.005)	(0.003)
cumulative repair	–	–	0.005	0.003	-0.002	0.007
			(0.0045)	(0.004)	(0.007)	(0.005)
engineers	–	–	–	0.04***	0.046***	0.03***
				(0.009)	(0.009)	(0.009)
observations	798	563	798	798	798	563
number of vessels	124	87	124	124	124	87
pseudo R^2	0.06	0.06	0.06	0.06	–	0.07
goodness of fit $\bar{\chi}^2$	684.1	377.9	679.2	659.3	–	368.9
year effects	yes	yes	yes	yes	no	yes
random ship effects	no	no	no	no	yes	no
LR test of random effects	–	–	–	–	27.15***	–

*** p<0.01, ** p<0.05, * p<0.1
bootstrap standard errors in parentheses

While we find evidence of complementarity for technology and capital for officers as well, the results appear smaller. In all specifications, coefficients on vessel age, displacement and ship length are noticeably smaller than the corresponding ones for engineers, yet still remain statistically significant. As previously discussed, however, we also observe a strong relationship between the total complement aboard vessels and the number of officers. This makes sense, as officers served a primary role as managers of sailors rather than direct operators of machinery. We also see positive associations between past years at sea for a vessel and the number of officers, while past repair experience of the vessel now has no discernible influence. This result appears in stark contrast to the engineer specifications. While engineers appeared needed on ships with long repair histories, line officers filled the roles on ships with extended tours of duty at sea.

6.1.3 Engineer intensity

Officers and engineers had very different functions on active vessels. To get a somewhat different perspective of the engineer skill intensity required on ships, we estimate the percentage of all skilled personnel on a ship who are engineers as the dependent variable. (Hence we estimate a measure of engineer personnel relative to officers.) Results from these specifications appear in table 5.

Unlike the poisson estimations, only the displacement variable demonstrates any statistical significance, but marginal effects remain small. As with poisson estimations, older vessels had smaller shares of engineers, but this result is statistically weak. Larger ship complements also implied a larger share of officers, a result also not surprising given previously discussed estimations. Lagrange multiplier tests reject the hypothesis for a pooled estimation. That is, there are *relatively* greater capital-skill and technology-skill complementarities with engineers than with officers.

These results are echoed in figure 3, where vessels are split into two groups of characteristics: large versus small ships, fast versus slow ships, old versus new. We subsequently chart the average share of engineers aboard each type for each year by each of these binary characteristics. Particularly for the 1890s (when the largest dispersion of old and new vessels steamed together), it clearly indicates that larger engineer shares are associated with heavier, longer, newer and faster ships.

In contrast to this, figure 4 plots the average experience of engineers who serving on a ship at any point in time. Quite clearly, by the 1890s, the most “experienced engineers” served on lighter, shorter and slower ships. If we consider that the most “experienced” engineers at this time often included those without Naval Academy technical training, or included engineers without an understanding of the latest technology, then this should not surprise. Newer, larger, longer and faster ships needed not only a larger cohort of engineers to operate them, they needed the younger and more technically proficient.

Table 5: FGLS random effects regressions for the percentage engineers on active vessel characteristics

VARIABLES	1	2	3	4	5	6
age of vessel	-0.002	-0.001	-0.001	-0.002*	-0.002	-0.002
	(0.0015)	(0.001)	(0.002)	(0.001)	(0.0015)	(0.001)
displacement (tons)	0.00002***	0.00002***	0.00002***	0.00002***	0.00002***	0.00002***
	(0.000008)	(0.000007)	(0.000007)	(0.000008)	(0.000008)	(0.000004)
length (feet)	0.0002	-0.00008	-0.00007	0.0003	0.0004	0.0002
	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0001)
complement (sailors)	-0.00016	-0.0001	-0.00007	-0.0002**	-0.00019*	–
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	
cumulative sea	-0.00001	–	-0.0008	–	0.0006	-0.0003
	(0.003)		(0.003)		(0.003)	(0.002)
cumulative repair	0.003	–	0.002	–	0.002	0.003
	(0.002)		(0.003)		(0.002)	(0.002)
decade 1870	0.045*	–	–	0.040*	0.049**	0.043**
	(0.023)			(0.021)	(0.023)	(0.018)
decade 1880	0.118***	–	–	0.118***	0.119***	0.111***
	(0.017)			(0.016)	(0.016)	(0.013)
constant	0.192***	0.289***	0.285***	0.181***	0.169**	0.174***
	(0.073)	(0.066)	(0.064)	(0.070)	(0.070)	(0.033)
observations	559	559	559	559	559	793
number of vessels	87	87	87	87	87	124
overall R^2	0.13	0.04	0.04	0.12	0.13	0.110
random ship effects	no	yes	yes	yes	yes	yes
lagrange multiplier test	–	14.47***	12.36***	9.17***	8.33***	4.64**

*** p<0.01, ** p<0.05, * p<0.1
bootstrap standard errors in parentheses
decade of 1890 omitted category

We also track the experience levels of engineers aboard active vessels (we have the start dates for the careers of every naval engineer through Bennett 1896). We use this to calculate the average experience level of all engineers serving aboard each ship as the dependent variable of panel regressions reported in table 6. Lagrange multiplier tests generally support the use of a random effects specification, while vessel age and displacement generate the most statistically robust results of all regressors.

Each year that ships age increase the average experience of engineer crews by one to five months. This result indicates that vintages of capital appear to match vintages of human capital and suggests an industry undergoing technological changes; perhaps this is an indication that only those engineers not invested in prior technological systems could effectively operate the new systems.

At the same time, more experienced engineer crews worked smaller ships, as suggested by negative coefficients on displacement. Newer and larger ships were manned by younger and larger groups of engineers, a result that we would expect in an environment with larger technology-skill complementarities.

Table 6: FGLS random effects regressions of average engineer experience on active vessel characteristics

VARIABLES	1	2	3	4	5	6
age of vessel	0.107**	0.438***	0.042	0.151***	0.111*	0.090*
	(0.050)	(0.060)	(0.099)	(0.040)	(0.057)	(0.047)
displacement (tons)	-0.0004*	-0.0009**	-0.0006**	-0.0006***	-0.0005**	-0.0008***
	(0.0002)	(0.0004)	(0.0003)	(0.0002)	(0.0002)	(0.0001)
length (feet)	-0.008	0.049***	0.039***	-0.0006	-0.0007	0.011*
	(0.007)	(0.016)	(0.012)	(0.007)	(0.007)	(0.006)
complement (sailors)	-0.0001	-0.0005	-0.005	0.0004	-0.002	–
	(0.003)	(0.007)	(0.006)	(0.003)	(0.003)	
cumulative sea	0.056	–	0.553***	–	0.108	0.132*
	(0.082)		(0.124)		(0.093)	(0.079)
cumulative repair	-0.133	–	0.282	–	-0.108	0.023
	(0.126)		(0.176)		(0.093)	(0.118)
decade 1870	-8.397***	–	–	-8.117***	-7.953***	-7.282***
	(0.728)			(0.561)	(0.733)	(0.694)
decade 1880	-5.810***	–	–	-5.763***	-5.625***	-5.654***
	(0.658)			(0.696)	(0.709)	(0.569)
constant	20.60***	0.202	4.82*	18.76***	18.995***	16.359***
	(1.495)	(2.954)	(2.616)	(1.555)	(1.707)	(1.478)
observations	530	530	530	530	530	748
number of vessels	87	87	87	87	87	124
overall R^2	0.482	0.064	0.154	0.473	0.478	0.477
random ship effects	no	yes	yes	yes	yes	yes
lagrange multiplier test	–	108***	141***	3.41*	3.05*	18.32***

*** p<0.01, ** p<0.05, * p<0.1
bootstrap standard errors in parentheses
decade of 1890 omitted category

6.2 Maintenance - vessels in repair

To examine the balance between factors in the repair and maintenance of naval vessels, we match those vessels repairing in navy yards with the numbers of officers and engineers assigned to those yards. We cannot directly match skilled labor to individual vessels, and personnel working in navy yards likely to performed a wide range of jobs, only some of which likely involved the repair of docked vessels. The results that follow, therefore, we take with a grain of salt, since estimates are not necessarily or directly defined by the operational demands of engineers or officers on ship under repair. Nevertheless, we produce some crude estimates of potential complementarities in vessel maintenance. The first set of results is displayed in table 7.

Table 7: Poisson regressions of number of engineers assigned to navy yards on repairing vessel characteristics

VARIABLES	1	2	3	4	5	6
average age	0.02***	0.02**	0.014***	0.01*	0.01	0.012
	(0.008)	(0.01)	(0.005)	(0.006)	(0.007)	(0.008)
# of repairing ships	0.47*	0.41	0.017	0.004	0.22	0.11
	(0.25)	(0.30)	(0.15)	(0.15)	(0.18)	(0.20)
total displacement	0.0002***	0.0002***	0.00009***	0.00005	0.00006*	0.00004
	(0.00004)	(0.00005)	(0.00002)	(0.00003)	(0.000035)	(0.00004)
total length	-0.003**	-0.003*	-0.0005	-0.00005	-0.001	-0.0006
	(0.0014)	(0.0017)	(0.0008)	(0.0009)	(0.001)	(0.001)
total cumulative sea	–	0.006	–	0.0003	–	0.01
		(0.008)		(0.006)		(0.008)
total cumulative repair	–	0.002	–	0.01	–	0.008
		(0.01)		(0.008)		(0.01)
observations	201	201	184	184	184	184
number of navy yards	12	12	10	10	10	10
pseudo R^2	0.30	0.30	–	–	–	–
poisson pooled	yes	yes	no	no	no	no
poisson fixed effects	no	no	yes	yes	yes	yes
year effects	yes	yes	no	no	yes	yes

constant and year effects not reported.
standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

For each navy yard with repairing ships, we construct annual measures of the total displacement of these ships, the total length of the ships, the total cumulative years (since 1870) that these vessels were at sea, and the total cumulative years (since 1870) that these vessels were being repaired.[11] As imprecise as these estimates may be, it is striking that technology-complementarity

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[11] We also aggregate some of these measures by weighting them according to displacement, including average year built. Results do not change.

measures for engineers move in the opposite direction as before. That is, older vessels require more engineers to repair them. Note that these results hold both with and without the inclusion of yard fixed effects.[12]

We also consider engineer intensity relative to officers in shipyards. For this, we regress the percent of engineers on yards relative to all skilled personnel and include year effects for all specifications. The results outlined in table 8 echo poisson regressions from table 7. Throughout the maintenance stage, a positive association remains between total ship displacement and engineer numbers. Furthermore older and slower vessels also require larger percentages of engineers to repair them.

The implication that newer and possibly more technologically advanced vessels required fewer skilled technicians for maintenance and repair supports our earlier stories concerning technology-skill complementarity. That is, naval technology appears skill-*replacing*; this result runs counter to the Goldin and Katz hypothesis, which would suggest that vessel maintenance would have required skill-intensive technologies. On the contrary, it rather appears that high-technology capital (e.g. especially newer and faster naval vessels) may be difficult to operate but fairly straight-forward to repair. Indeed this story remains true even in today's increasingly technological Navy, where relatively high-skill personnel (officers) operate and coordinate the operation of the complicated machinery on ships and aircraft, but relatively low-skill personnel (enlisted sailors) are charged with the occupations of repair and day-to-day maintenance.

7 Conclusion

As the nation proceeded through the second industrial revolution during the latter 19th century, naval vessels became increasingly more technical. The most advanced vessels (faster, heavier and newer) required larger shares of technically-proficient workers for operation but relatively fewer for maintenance. At the same time, we observe relatively fewer *worker*-skill complementarities with engineers than with officers. Officers retained comparative advantage in managing the complement of laborers at sea. Skilled workers were highly specialized, and the late-19th century Navy was one where complementarities abounded.[13]

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[12] We also have the number of naval constructors in each yard as an additional potential skilled-labor group. We find no statistically significant relations between the number of constructors and repairing vessel characteristics.

[13] Such inferences can only be made indirectly for this time period. Details on the task content of specific occupations are typically not available for the 19th century (the first edition of the *Dictionary of Occupational Titles* which would have such information was published in 1939).

Table 8: Regressions of engineer-percent assigned to navy yards on repairing vessel characteristics

VARIABLES	1	2	3	4	5	6
average speed	-0.02***	-0.016***	-0.018***	-0.01**	-0.008	-0.009
	(0.006)	(0.006)	(0.006)	(0.005)	(0.007)	(0.007)
average age	–	0.001	0.0003	–	0.0037*	0.003
		(0.002)	(0.002)		(0.002)	(0.002)
# of repairing ships	0.02	0.02	0.03	0.04	0.04	0.03
	(0.06)	(0.06)	(0.06)	(0.04)	(0.04)	(0.05)
total displacement	0.00002**	0.00002**	0.00003***	0.00002***	0.00002***	0.00003***
	(0.00001)	(0.00001)	(0.00001)	(0.000007)	(0.000007)	(0.000009)
total length	-0.0003	-0.0003	-0.0003	-0.0003	-0.0003	-0.0003
	(0.0003)	(0.0003)	(0.0004)	(0.0003)	(0.0002)	(0.0003)
total cumulative sea	–	–	0.002	–	–	0.002
			(0.002)	–	–	(0.002)
total cumulative repair	–	–	-0.002	–	–	-0.0006
			(0.002)			(0.003)
observations	142	142	142	142	142	142
number of navy yards	8	8	8	8	8	8
R^2	0.47	0.47	0.48	0.47	0.47	0.47
pooled	yes	yes	yes	no	no	no
yard fixed effects	no	no	no	yes	yes	yes

Constant and year effects not reported.
Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

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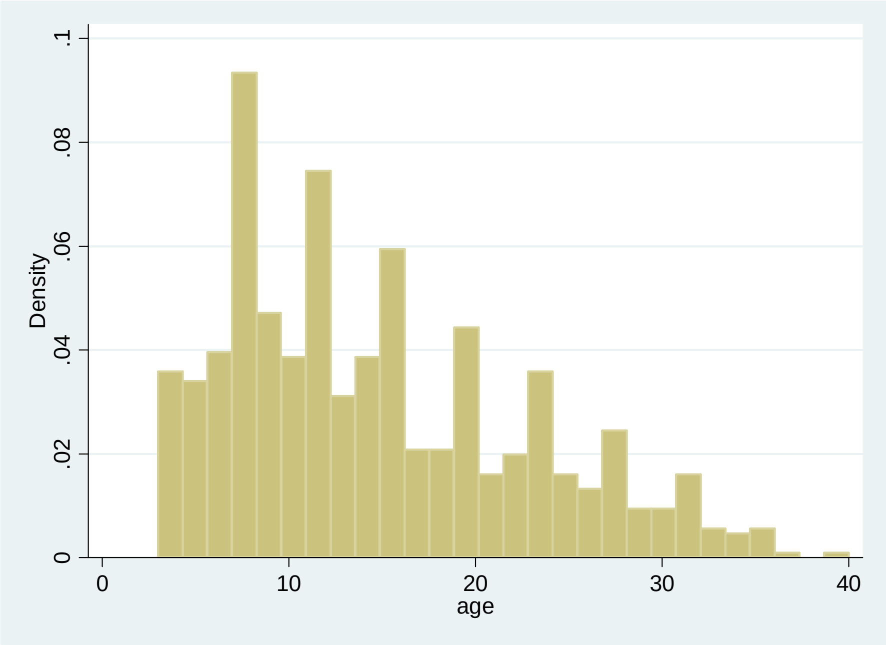
Figure 1: Age profiles of naval vessels

Age of all active vessels across all years



Average age of all repairing vessels docked in navy-yards across all years

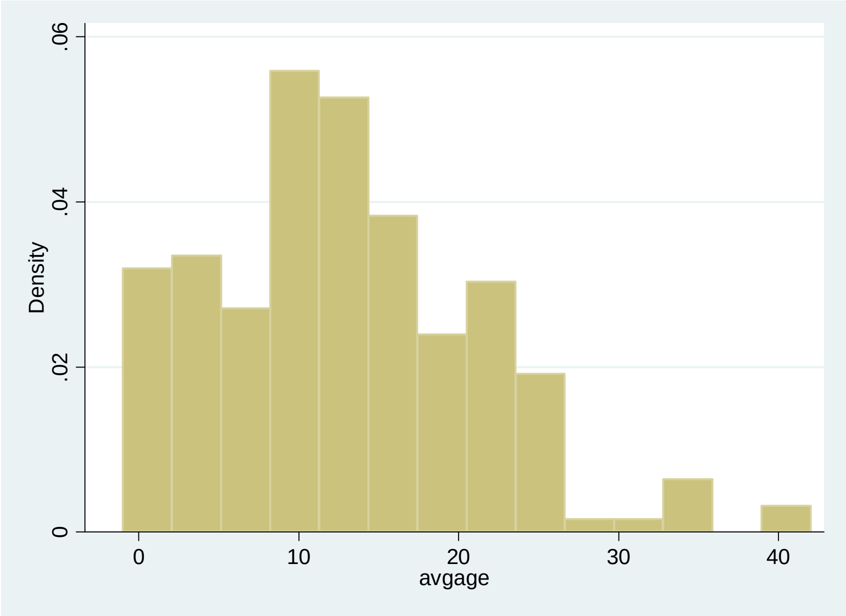
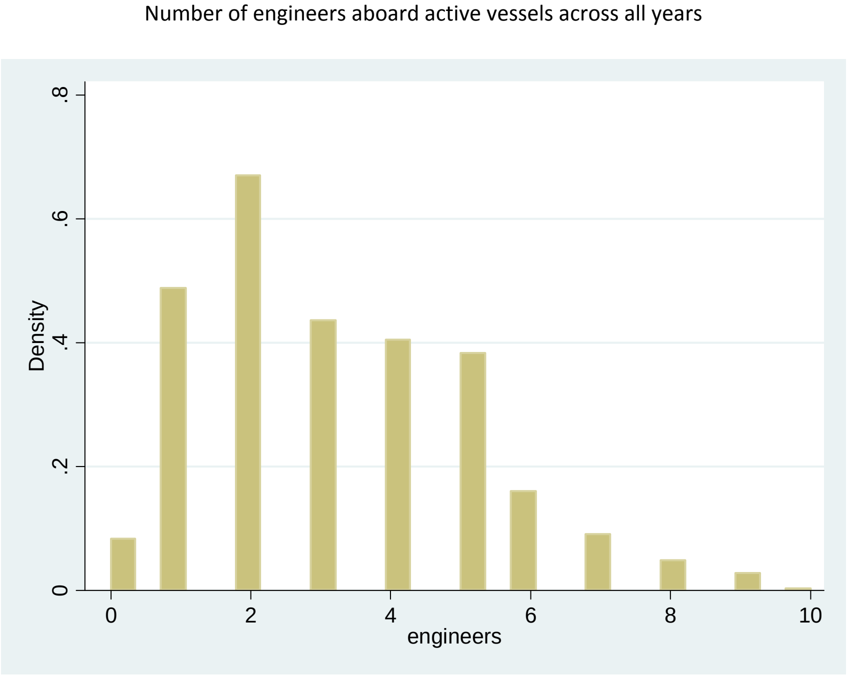


Figure 2: Numbers of skilled labor on active vessels



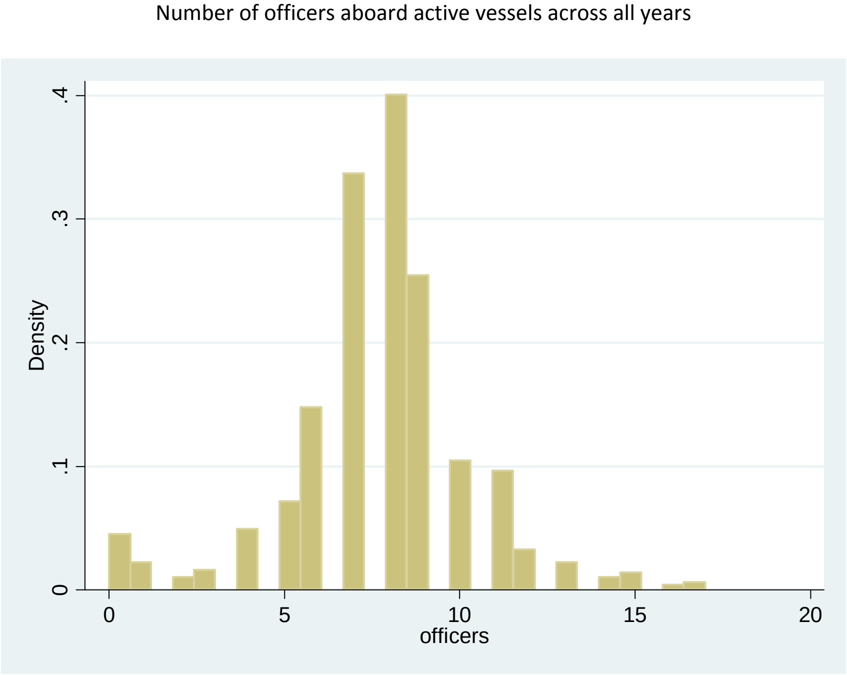


Figure 3: Share of engineers (relative to all skilled personnel) on active vessels, year by year

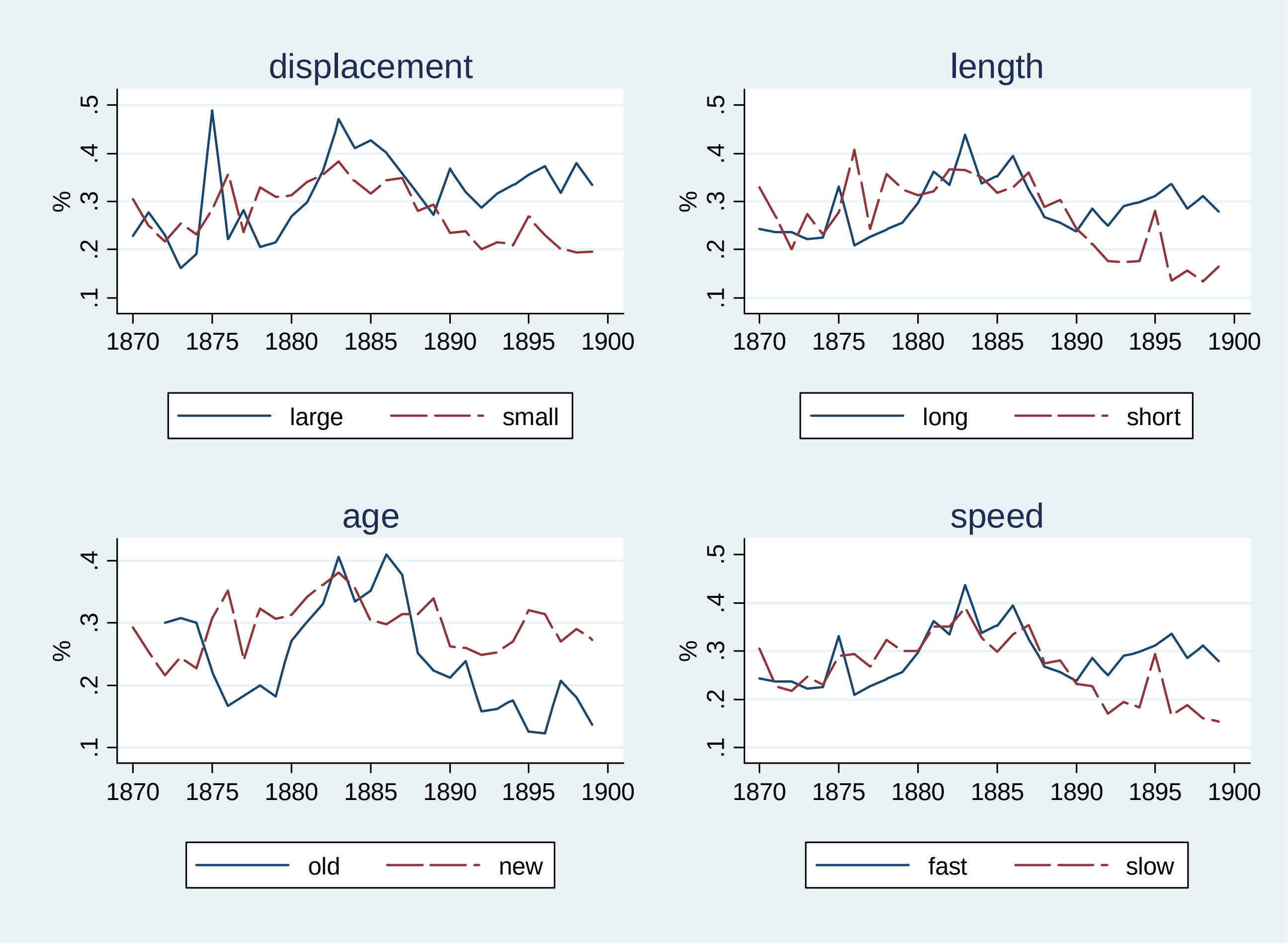


Figure 4: Experience of engineers on active vessels, year by year