# Naval Engineering and the Origins of Technology-Skill Complementarity

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May 2011

**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. We exploit a unique dataset that contains the names and characteristics of every serving naval officer and 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 skilled laborers 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 findings suggest that more technically skilled workers served on larger and more technologically advanced vessels, while less technically-skilled officers worked more with unskilled personnel. At the same time, fewer technically skilled workers were needed to repair and maintain these technologically advanced ships. Naval technological developments run counter to Goldin and Katz's findings. Maintenance and repair became skill-saving while production became skill-using.



- *Keywords*: skilled-labor complementarity, skill-replacing and 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) document capital-skill complementarities 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 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 two distinct and sequential stages, a machine-installation and maintenance stage, and a production stage. There are two kinds of skilled workers: naval line officers (who act as managers) and naval engineers (who act as technocrats); these skilled laborers work with technology-embodied capital (the naval vessel) and unskilled labor (the vessel's complement of sailors). 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

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

[2]See for example Glaser and Rahman, forthcoming. Some words of caution from a military historian are worth noting - "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.

complementarities with capital, raw labor, evolving naval technology, and each other. What we find should not be very different from the productive relations between inputs in other highly complex industries during this period. We also wish to observe these relationships during the maintenance or implementation of capital stage separately from the actual production stage. Insights we gleam can help us better understand multi-stage production processes in 19th century industry.

Our analysis finds a number of things. First, there are very clear capital-skill and technology-skill complementarities in production. More specifically, proxies for technology and naval capital positively affect the numbers of both officers and engineers assigned to active vessels (we refer to these as *weak* officer- and engineer-complementarities). Further, these proxies also positively affect the number of engineers *relative* to officers (we refer to this as *strong* engineer-complementarity). On the other hand, officers appear to strongly complement *unskilled* labor in production on active ships. These results highlight the importance in distinguishing between different types of human capital - 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 and installation portion of production; if anything technologically-advanced vessels require fewer engineers to repair. This result suggests that naval production does not fit the Goldin and Katz framework, where skilled-labor is increasingly needed in machine-installation and maintenance activities. In this industry, production itself requires an understanding of complex systems and the use of more technocrats for proper execution and implementation (in contrast to assembly-oriented production typical of manufacturing). Perhaps other service-oriented industries of the 19th century behaved similarly, or perhaps instead the Navy simply intimated 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 sections 4 and 5 describe how we empirically test this framework with the data we have. Section 6 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 provides us with a unique opportunity to examine the use of capital, since each vessel embodied 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 to emulate the British Royal Navy, 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 bold changes 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 thus began its attempts to converge to the technological frontier in earnest by the 80s; for example in 1886 American officers made technical pilgrimages to Europe, 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 built and launched were radically different in both design and ability. In fact to some, "the new navy [was] one so different from much that [had] preceded...as to make it a subject by itself, only slightly connected with all that [had] 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 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 failed to get a clear 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 manifest. 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. 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

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

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 pecuniary 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 officers and engineers had radically different functions. 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 these two types of skilled workers separately in both the maintenance and the usage of vessels.[5]

[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 between labor of different servitude-status or gender.

# 3 Conceptual Framework

We start with 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 human capital-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.

To motivate the analysis, let us imagine a navy with an objective to maximize "sea-power projection" over multiple periods of time. That is, the navy wishes to consistently maintain as many vessels in international waters as possible. This framework of production is consistent with the views of the late nineteenth century, during which time naval duties were generally devoted to "showing the flag." Implicitly, naval "production" served to protect American commerce and its agents in the international arena (Buhl, 1978). For the sake of simplicity, we consider the two-period case with an objective function

$$\max \ \log Q_1 + \log Q_2 \ , \tag{1}$$

where $Q_i$ is a measure of naval power projection in period $i$. Power projection requires linking usable capital (sea-worthy vessels) with human capital. We describe $Q_i$ as

$$Q_i = [(A_k K_i^*)^\rho + (A_h H_{iQ})^\rho]^{\frac{1}{\rho}} \tag{2}$$

where $K_i^*$ captures the stock of usable vessels in period $i$, $H_{iQ}$ is a measure of skilled personnel assigned to sea duty in period $i$, and the parameter $\rho \leq 1$ governs the degree of elasticity between ships and personnel in sea power (the actual elasticity is $\frac{1}{1-\rho}$). $A_k$ and $A_h$ are vessel- and personnel-augmenting technologies, respectively.

The primary choice involves the number of skilled personnel assigned to sea duty in period 1 (thus bolstering power projection in period 1) versus the numbers of skilled personnel assigned

[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.

to maintenance and repair (thus bolstering usable capital and power projection in period 2). We assume that while $K_1^*$ is exogenous (the navy inherits usable ships in period 1), $K_2^*$ is given by the relationship

$$K_2^* = \left[ (B_k K)^\theta + (B_h H_K)^\theta \right]^{\frac{1}{\theta}} \tag{3}$$

$K$ is "raw capital" - those ships under repair (we consider this to be exogenous as well). $H_K$ measures those skilled workers assigned to ship repair. $\theta$ governs the degree of complementarity between repairing ships and skilled personnel.

Here we argue that line officers and engineers were not substitutable at all during this period, since line officers had no idea about the workings of steam technologies. In 1839, Commander R. S. Robinson of the Royal Navy writes,[7]

> *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.*

We thus assume perfect complementarities between officers and engineers, and specify the following measures for human capital:

$$H_{1Q} = \min \left[ \lambda O_q, \lambda E_q \right] \tag{4}$$

$$H_K = \min \left[ \lambda O_k, \lambda E_k \right] \tag{5}$$

$$H_{2Q} = \min \left[ \lambda O, \lambda E \right] \ , \tag{6}$$

where $O = O_q + O_k$ is the total number of officers split in period 1 between those on active ships ($O_q$) and those in repair ($O_k$). Similarly, $E = E_q + E_k$ is the total number of engineers split in period 1 between those on active ships ($E_q$) and those in repair ($E_k$). All skilled personnel work on active vessels in period 2, given that there is nothing at that point to repair.

[7] Taken from Smith (1937), *Nautical Steam Engine Explained and its Powers and Capabilities Described for the Use of the Officers of the Navy.*

Given its labor constraints, the navy chooses $O_k$ and $E_k$ in order to meet its objective in (1). This entails first order conditions for (1) with respect to $O_k$ and $E_k$, given total supplies of $K_1^*$, $K$, $O$ and $E$. While these functional forms do not allow for closed-form solutions, we can numerically plot optimal allocations of skilled personnel, and see how parameter changes can alter these.

First, we assume that $O > E$, so that engineers are the binding skilled labor in (4) - (6) (analogous results would apply for $O < E$). Next, since naval technological developments imply capital-augmenting technical change, we would be interested in seeing how the allocation of engineers would change with increases in $A_k$. Finally, since much naval history discusses the increasing importance of skilled personnel on seagoing vessels, we would also like to see how allocations change with *decreases* in $\rho$ (that is, with rising complementarities between vessels and skilled personnel in sea voyages).

Numerical solutions of these exercises are presented in figures 1 and 2.[8] The first diagrams demonstrate how capital-augmenting technical change drives the navy to supply more engineers to naval "production." In the first case we set $\rho = -10$ to assume a high degree of complementarity between vessels and human capital. With such complementarity and engineers being in relative scarce supply, the navy matches more productive capital in production with more engineers in production. Of course this leads to less capital for production in period 2, but this is offset by the fact that this capital is more productive, and so both $Q_1$ and $Q_2$ are larger.

We also demonstrate the allocative effects of capital-augmenting technical change assuming that capital and skills are grossly *substitutable* (here we set $\rho = 0.5$, thereby assuming an elasticity of factor substitution of two). Strikingly, technological growth still generates greater labor allocation to production. Why? Clearly as capital gets more productive here, the gains from increasing the workforce in production are more limited than in our prior case. But $Q_2$ now is much higher relative to $Q_1$ (since all those engineers who were working in maintenance during period 1 work in production in period 2, and they are all much more productive given their substitutability with capital). It therefore makes sense to divert some resources to generate more

[8]Parameters are set as follows: For the evolution of $A_k$, all other technologies, $A_h$, $B_k$, $B_h$ are set to 1. Furthermore $K = 0.5$, $K_1^* = 1$, $O = 4$, $E = 2$, $\lambda = 0.5$, and $\theta =$ -10. For the second exercise developing the evolution of $\rho$, we set $A_k = 1$. Qualitative results are robust to all parameter values $\theta < 1$. Qualitative results are also not sensitive to our choice of technology levels.

$Q_1$ at the expense of some $K_2^*$. Thus we see that in this model, capital-augmenting technological advance will increase the number of skilled personnel to production for all *plausible* degrees of factor substitutability.[9] Simply stated, the model suggests rather robustly that more advanced naval vessels will require more engineers to operate them.[10]

Figure 2 illustrates what happens to allocations when the degree of complementarity between active ships and personnel itself strengthens. In particular, greater complementarity raises the demands for engineers serving aboard active vessels, albeit at a diminishing rate. Also notice that in all cases greater use of engineers in production necessarily pulls engineers away from maintenance. Thus we see that skill-replacement in maintenance would be consistent with greater capital-skill or technology-skill complementarities in production.

Note that our empirical exercises in the next sections will not allow us to quantitatively isolate each parameter, or the changes in each parameter over time. If we observe a rise in engineers aboard active vessels over time, we might attribute this to a rise $A_k$, or to a fall in $\rho$, or to both, or to some other parameter change - without further structural restrictions we cannot tell from the data. The above suggests that potential complementarities in maintenance and production can arise for a variety of reasons. The empirics that we present below attempt to document these complementarities without pinpointing their precise source.

# 4 Empirical Framework

To estimate relationships in the conceptual framework outlined in section 3 with reduced form specifications, we regress alternative measures of skilled labor and skill-intensity levels on a set of ship and shipyard characteristics.

## 4.1 Engineer and officer counts

To estimate the effects of capital and technology on the number of skilled workers assigned to specific jobs (either aboard ships or in shipyards), we define $y$ as a non-negative count variable

[9] Only when factor substitutability reaches beyond 5 or more would increases in $A_k$ imply lower $E_q$.

[10] As Acemoglu (2007) suggests, capital-augmenting technological progress should *decrease* the relative demand for labor in a two-factor production process when capital and labor are grossly substitutable. Multi-period problems, such as those faced by the Navy and other industries, can complicate this finding.

with integer values $0, 1, 2, ....$ Specifically this represents the total number of engineers or officers assigned to ships and shipyards. 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 4 provides further motivation for the assumption of a poisson model. Following Wooldridge (2002), the conditional mean given the vector $\mathbf{x}$ is defined $E(y|\mathbf{x}, \eta; \beta) = exp(\mathbf{x}\beta)\eta$. Initially, we assume $E(\eta|\mathbf{x}) = E(\eta) = 1$, which implies that standard quasi-maximum likelihood techniques (QML) consistently estimate the parameters of the model. Our interest is in the $K \times 1$ vector of parameters in $\beta$.[11] Results from these regressions are reported in tables $3 - 5$ for ships serving at sea and table 8 for ships under construction or repair in shipyards.

#### 4.1.1 Endogenous engineer and officer counts

While convenience leads one to assume statistical independence of $\eta$ and $\mathbf{x}$, our conceptual framework allows for the possibility that ship allocations of officers and engineers are both endogenous variables. In particular, the lack of substitutability in skilled labor suggests a failure of the assumption for conditional mean independence, which means $E(\eta|\mathbf{x}) \neq E(\eta)$. Mullahy (1997) details how standard QML techniques produce inconsistent estimates of $\beta$ when this assumption fails; however, he also outlines estimation methods using two-stage QML and GMM techniques that mitigate the endogeneity problem and generate more consistent parameter estimates.

Similar to IV specifications found in standard contexts, our IV specifications will need a $p \times 1$ vector of exogenous instruments, $\mathbf{z}$, where $p \geq K$. The $p$ instruments may include elements of $\mathbf{x}$ not correlated with $\eta$. We report estimates of IV estimations following from these methods in table 5.

### 4.2 Engineer intensity

We also exploit the panel structure of the data to evaluate how changes in the capital and technological characteristics of ships lead to changes in the mix of skilled workers serving on ships and in shipyards. Which attributes led stations to rely on more experienced (and possibly less technically savvy) engineers? What causes the share of engineers relative to line officers in

[11] We also include parameters estimated under poisson specifications with random effects.

various stations to change over time? In both cases, we uncover the factors that change labor skill intensity.

The unobserved effects model estimates engineer intensity or average engineer experience over time following the specification

$$y_{it} = x_{it}\beta + c_i + u_{it} , \qquad t = 1, 2, ...., T . \tag{7}$$

The random variable $c_i$ controls for unobserved heterogeneity and improves estimate efficiency in the $K \times 1$ vector $\beta$. By construction, estimates follow from the assumption that $c_i$ is not correlated with $x_{it}$. Results from FGLS estimation of engineer intensity on ships using (7) appear in table 7.

# 5 Data

Our core empirical strategy regresses measures of skilled personnel 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 annual volumes published by the United States Navy document 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 (location/tour) 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.[12]

Vessels under repair or being newly constructed typically 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 vessels under construction or repair docked in those same yards. We also construct aggregate measures of ship characteristics under repair in these yards during particular years. This helps build longitudinal data, where time is measured at the yard-year level.

[12]For example, a vessel could be stationed in the Pacific for five years while the officer and engineer counts aboard vessels vary year to year as the ship docks at ports and personnel change stations.

Primary data extracted from the Navy Registers is matched 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 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, the Dictionary of Fighting Ships, augments ship information in Bennett (1896). This also includes newer vessels and other vessel traits such as the complement (the number of sailors and other crew members) and ship cruising speeds.

The 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 generates a wide range of steam vessel-types and enables us to track 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 3). 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. Descriptive statistics for ship characteristics of vessels active in naval power projection (at sea) appear in table 1.

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.[13]

Figure 6 provides more perspective on the changing roles of engineers on ships and in shipyards during our era. In particular we see that the age of ships at sea and in shipyards closely parallel the intensity of engineers within these two occupations. We also see that the number of officers serving on ships remains relatively stable across time with minor fluctuations. During the 1880s, however and compared to other decades, more engineers serve at sea. As the fleet received an influx of new physical capital during the 1890s, many engineers move into shipyards in support of ship repairs for the aging segment of the fleet. This is consistent with predictions generated in our model, where lower $A_k$ (as one expects on older ships) requires higher $E_m$.

[13]Particularly important is controlling for the build-up and draw-down of battle readiness from 1897 to 1899 due to the Spanish-American War.

As we show with the empirical results, these visual depictions do not actually indicate the full complexity of the labor allocation problem. Among other things, the empirical results demonstrate how officers and engineers share a great deal of complementarity in naval duties; these results appear robust across specifications and regardless of duty (at sea or in a station). Certainly the age of vessels matter, but the type of ship and even the experience of the engineers all play important roles in the Navy's allocation of labor.

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 |
| cumulative time at sea | 802 | 5.97 | 5.01 | 1 | 29 |
| cumulative time under repair | 802 | 2.59 | 2.76 | 0 | 22 |

Table 2: Average characteristics of ships docked in shipyards

| ship characteristics | observations | mean | standard deviation | minimum | maximum |
|---|---|---|---|---|---|
| average age | 150 | 14.2 | 7.9 | 0 | 42 |
| average maximum speed (knots) | 142 | 11.5 | 2.2 | 5.5 | 18.6 |
| average displacement (tons) | 150 | 2397.1 | 1175.6 | 418 | 6300 |
| average length (feet) | 150 | 228.9 | 33.3 | 90 | 301 |
| engineers per ship | 150 | 2.23 | 1.29 | 0 | 6 |
| officers per ship | 150 | 5.11 | 3.60 | 0.6 | 18 |
| civil engineers per ship | 150 | 0.61 | 0.48 | 0 | 3 |

# 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 4, while descriptive statistics for variables included in all regressions appear in tables 1 and 2. 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. Some specifications (indicated on each table) include cohort interactions, which are combinations of vessel ages and the year dummy variables. These essentially capture and control for the vintage of ships. For example, a 5 year old ship observed in 1880 likely has less advanced technology than a 5 year old ship observed in 1885. Finally, given the heterogeneity in our sample of vessels (e.g. some ships as small as 16 feet long, with others as large as 411 feet long), we control for additional non-linearities in technology using quadratic regressors. These allows us capture points at which expanding demand for engineers on vessels begin to level-off.

#### 6.1.1 Engineer counts and weak complementarity

Table 3 presents results for engineer counts serving on active ships at sea, the estimates of which derive from the empirical methodology outlined in section 4.1. In pooled regressions, estimates support our basic hypotheses for the presence of weak technology-skill and capital-skill complementarities in naval activity. On active vessels, displacement and length positively affect the roll of engineers. Columns (1)-(3) do not include cohort effects to control for vintage. In these specifications, age negatively relates to the number of engineers assigned to the ship. 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 skilled labor. 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 in columns (5) should be more efficient than pooled regression, but still may run the risk of omitted variables, eroding the unbiasedness of estimates.

We also exploit the panel structure of the data through specifications shown in columns (4)-(6). These estimations include controls for interactions on the vintage of a vessel at different points in time. For most specifications, chi-squared tests support the inclusion of age-cohort interactions.[14] Regardless of their vintage, older ships always require fewer engineers than newer vessels. That is, 5-year-old vessels in 1884 require more engineers than 10-year-old vessels in 1884, and 5-year-old vessels in 1899 requires more engineers than 10-year-old vessels in 1899. Intercepts and slopes, however, do not remain consistent *and* do not show any trend across time. For example, 10-year old vessels in 1894 require fewer engineers than similarly aged vessels in 1884 but more than similarly aged vessels in 1899. A snapshot of these vintage effects (based on the results from column (6) of table 3) appears as figure 5.

Ships that receive numerous repairs prior to voyage (cumulative repair) consistently require

[14]The authors will provide complete set of results for the vintage interaction coefficients upon request. Each chi-squared test is based on 30 degrees of freedom.

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. The results in column (6) indicate that each additional officer increases the need for an additional engineer by approximately ten percent. These results are also likely endogenous, which we explore further with IV regressions in a later section of the paper.[15]

One might consider the use of a vessel's age as a proxy for technology, $A_k$. 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 might give us a sense of the technological vintage of the vessel. As figure 5 indicates, however, these vintage effects shift over time. The only consistently clear pattern (a negatively sloped function) indicates that during any given year, older ships had fewer engineers. Given the shifting demand due to vintage, however, we need a more overt measure of the technical capability of a vessel.

Along with improved fuel efficiency, a primary goal for the improvement of steaming technology was to increase the potential cruising speed of a vessel. We have this information for only 80% of the sample of vessels. Although this leaves a sizeable chunk of missing information, we include results with potential ship speed in table 4.

These alternative specifications provide a somewhat more clear indication of the complementarity between technology and engineering-skill on active vessels. Controlling for age, an extra knot of speed is associated with increases in engineering personnel. The quadratic effects shown in column (6) indicate a strong positive effect for the majority of vessels with potential speeds in excess of the tipping point (approximately 10 knots). That is, as vessel speed potential exceeds beyond 10 knots, demand for engineering skill increases quadratically.

Even after controlling for the speed (i.e. propulsion technology) of the vessel, a decline in engineering personnel continues to persist for every year that vessels age. Although we do not report the estimates for the 29 additional age-cohort interaction terms, the reader can be assured that these estimates echo the results shown in figure 5.[16] We also observe robust positive effects

[15]Notably the inclusion of regressors for ship's "complement" and/or "complement-squared" (i.e. number of sailors) in similar specifications for regressions in table 3 and 4 never appear statistically significant. We use this as a justification to use these variables as instruments for the *officers* variable.

[16]Again, the authors will provide estimates of interaction coefficients upon request.

on engineer numbers from the size of ships. Longer and heavier ships demanded more engineers during active periods. These quadratic coefficients appear quite small but statistically significant, and if anything indicate a leveling-off of the demand for engineers rather than a shift in direction of the relationship as ships grew in size.

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

| VARIABLES | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| age of vessel | -0.012*** | -0.018*** | -0.015*** | -0.031 | -0.032 | -0.039 |
| | (0.0027) | (0.003) | (0.003) | (0.007) | (0.026) | (0.029) |
| age-squared | - | - | - | - | - | 0.0003 |
| | | | | | | (0.0004) |
| displacement (tons) | 0.0001*** | 0.0001*** | 0.00008*** | 0.00007*** | 0.00007*** | 0.0003*** |
| | (0.00001) | (0.00001) | (0.00001) | (0.00002) | (0.00002) | (0.00004) |
| displacement-squared | - | - | - | - | - | -1.96e-8*** |
| | | | | | | (3.16e-9) |
| length (feet) | 0.003*** | 0.003*** | 0.003*** | 0.003*** | 0.003*** | 0.003*** |
| | (0.0005) | (0.0004) | (0.0004) | (0.0005) | (0.001) | (0.001) |
| length-squared | - | - | - | - | - | -5.7e-6** |
| | | | | | | 2.3e-6 |
| cumulative sea | – | 0.012** | 0.009 | 0.020*** | 0.025** | 0.055*** |
| | | (0.005) | (0.006) | (0.007) | (0.011) | (0.013) |
| cumulative sea-squared | - | - | - | - | - | -0.002*** |
| | | | | | | (0.0006) |
| cumulative repair | – | 0.023*** | 0.022*** | 0.032*** | 0.032** | 0.042*** |
| | | (0.006) | (0.006) | (0.008) | (0.013) | (0.014) |
| cumulative repair-squared | - | - | - | - | - | -0.001* |
| | | | | | | (0.0007) |
| officers | – | – | 0.045*** | 0.044*** | 0.039*** | 0.091** |
| | | | (0.011) | (0.010) | (0.011) | (0.037) |
| officers-squared | - | - | - | - | - | -0.004** |
| | | | | | | (0.002) |
| observations | 798 | 798 | 798 | 798 | 798 | 798 |
| number of vessels | 124 | 124 | 124 | 124 | 124 | 124 |
| pseudo $R^2$ | 0.15 | 0.15 | 0.16 | 0.17 | – | 0.18 |
| year effects | yes | yes | yes | yes | yes | yes |
| age*cohort interactions | no | no | no | yes | yes | yes |
| $\chi^2$ of age*cohort interactions | – | – | – | 49.8*** | 46.0** | 42.3* |
| random ship effects | no | no | no | no | yes | no |
| LR test of random effects | – | – | – | — | 4.14** | – |

standard errors shown in parentheses, bootstrap estimators except in random effects specifications
*** p<0.01, ** p<0.05, * p<0.1

Table 4: Poisson regressions of engineers assigned to active vessels on vessel characteristics (inc. speed)

| VARIABLES | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| speed of vessel (knots) | 0.020** | 0.026*** | 0.019* | 0.009 | 0.009 | -0.101*** |
| | (0.010) | (0.010) | (0.010) | (0.011) | (0.015) | (0.041) |
| speed-squared | - | - | - | - | - | 0.005*** |
| | | | | | | (0.002) |
| age of vessel | -0.010*** | -0.016*** | -0.014*** | -0.033 | -0.035 | -0.007 |
| | (0.003) | (0.003) | (0.003) | (0.025) | (0.027) | (0.028) |
| age-squared | - | - | - | - | - | -0.0004 |
| | | | | | | (0.0005) |
| displacement (tons) | 0.0001*** | 0.0001*** | 0.0001*** | 0.0001*** | 0.0001** | 0.0004*** |
| | (0.00002) | (0.00002) | (0.00002) | (0.00002) | (0.00002) | (0.0001) |
| displacement-squared | - | - | - | - | - | -1.9e-8*** |
| | | | | | | (4.2e-9) |
| length (feet) | 0.003*** | 0.003*** | 0.003*** | 0.003*** | 0.003*** | 0.006*** |
| | (0.0004) | (0.0005) | (0.0006) | (0.0005) | (0.0009) | (0.001) |
| length-squared | - | - | - | - | - | -0.00002*** |
| | | | | | | (4.1e-6) |
| cumulative sea | – | 0.013** | 0.009 | 0.016** | 0.022* | 0.041*** |
| | | (0.007) | (0.006) | (0.008) | (0.012) | (0.0006) |
| cumulative sea-squared | - | - | - | - | - | -0.001* |
| | | | | | | (0.0006) |
| cumulative repair | – | 0.027*** | 0.025*** | 0.032*** | 0.033** | 0.030* |
| | | (0.008) | (0.005) | (0.010) | (0.014) | (0.017) |
| cumulative repair-squared | - | - | - | - | - | -0.0009 |
| | | | | | | (0.0008) |
| officers | – | – | 0.041*** | 0.047*** | 0.041*** | 0.100*** |
| | | | (0.010) | (0.009) | (0.012) | (0.032) |
| officers-squared | - | - | - | - | - | -0.005*** |
| | | | | | | (0.002) |
| observations | 676 | 676 | 676 | 676 | 676 | 676 |
| number of vessels | 103 | 103 | 103 | 103 | 103 | 103 |
| pseudo $R^2$ | 0.15 | 0.15 | 0.16 | 0.17 | – | 0.18 |
| year effects | yes | yes | yes | yes | yes | yes |
| age*cohort interactions | no | no | no | yes | yes | yes |
| $\chi^2$ of age*cohort interactions | – | – | – | 119*** | 29.4 | 165*** |
| random ship effects | no | no | no | no | yes | no |
| LR test of random effects | – | – | – | – | 2.90** | – |

standard errors shown in parentheses, bootstrap estimators except in random effects specifications
*** p<0.01, ** p<0.05, * p<0.1

### 6.1.2 Officer counts and weak complementarity

Conceivably the kinds of skills officers provided differed from engineers, particularly prior to the Amalgamation Act after which all line officers were required to have engineering competence. To test for differences, we estimate poisson specifications for the number of officers on active vessels and present these in table 5.

While we find evidence of weak complementarity for technology and capital for officers as well, the results appear much weaker than those for engineers. In all specifications, coefficients on vessel age, displacement and ship length are either noticeably smaller than the corresponding ones for engineers or insignificant. 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 as 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 ships with long repair histories appear to require more engineer labor, line officers filled the roles on ships with extended tours of duty at sea.

Table 5: Poisson regressions of officers assigned to active vessels on vessel characteristics

| VARIABLES | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| age of vessel | -0.002* | -0.006*** | -0.006*** | -0.011 | -0.011 | -0.014 |
| | (0.0013) | (0.002) | (0.002) | (0.017) | (0.014) | (0.015) |
| age-squared | - | - | - | - | - | 0.00005 |
| | | | | | | (0.0002) |
| displacement (tons) | 0.00005*** | 0.00006*** | -0.00001 | -0.00002 | -0.00002 | 0.0001** |
| | (0.00001) | (0.00001) | (0.00001) | (0.00001) | (0.00002) | (0.00004) |
| displacement-squared | - | - | - | - | - | -7.1e-9** |
| | | | | | | (3.1e-9) |
| length (feet) | 0.001*** | 0.0014*** | -0.0002 | -0.00008 | -0.00008 | -0.00005 |
| | (0.0003) | (0.0003) | (0.0004) | (0.0005) | (0.0007) | (0.002) |
| length-squared | - | - | - | - | - | -2.2e-6 |
| | | | | | | (2.8e-6) |
| cumulative sea | – | 0.01*** | 0.009** | 0.011** | 0.011 | 0.013 |
| | | (0.003) | (0.004) | (0.004) | (0.007) | (0.010) |
| cumulative sea-squared | - | - | - | - | - | -0.0001 |
| | | | | | | (0.0004) |
| cumulative repair | – | 0.005 | 0.007 | 0.008 | 0.008 | 0.007 |
| | | (0.0045) | (0.006) | (0.007) | (0.008) | (0.011) |
| cumulative repair-squared | - | - | - | - | - | -0.0003 |
| | | | | | | (0.0008) |
| engineers | – | – | 0.027*** | 0.028** | 0.028** | 0.044 |
| | | | (0.010) | (0.012) | (0.012) | (0.032) |
| engineers-squared | - | - | - | - | - | -0.004 |
| | | | | | | (0.003) |
| complement (sailors) | – | – | 0.001*** | 0.001*** | 0.001*** | 0.003*** |
| | | | (0.0002) | (0.0002) | (0.0002) | (0.0006) |
| complement-squared | - | - | - | - | - | -2.5e-6*** |
| | | | | | | (7.2e-7) |
| observations | 798 | 798 | 563 | 563 | 563 | 563 |
| number of vessels | 124 | 124 | 87 | 87 | 87 | 87 |
| pseudo $R^2$ | 0.06 | 0.06 | 0.07 | 0.07 | – | 0.08 |
| year effects | yes | yes | yes | yes | yes | yes |
| age*cohort interactions | no | no | no | yes | yes | yes |
| $\chi^2$ test of age*cohort interactions | – | – | – | 33.0 | 12.4 | 43.6** |
| random ship effects | no | no | no | no | yes | no |
| LR test of random effects | – | – | – | – | 0.0003 | – |

standard errors shown in parentheses, bootstrap estimators except in random effects specifications
*** p<0.01, ** p<0.05, * p<0.1

### 6.1.3 Instrumental variable strategy

As discussed in section 4.1.1 and outlined in Mullahy (1997), poisson specifications with an endogenous variable produce biased estimates. In particular, the number of officers on a ship is likely endogenous in engineer regressions. Following Wooldridge (2002), we can confirm the endogeneity of officers by first estimating the residuals from an OLS regression of *officers* on *age*, *displacement*, *length*, *cumulative sea* and *cumulative repairs*, *complement*, as well as cohort and time effects. We then estimate a poisson regression similar to column (4) of table 3 and include the residuals from the first stage as an additional covariate. The p-value associated with these residuals in the second stage equals 0.002, a result that makes it appear desirable to use IVs.

We use the *complement* (the number of enlisted sailors) of a ship as an instrument and justify this based on two claims. First, *complement* is a rather strong predictor of the number of officers on a vessel. In fact, it is the only robust predictor of the number of officers assigned to a vessel in OLS specifications. As table 5 highlights, most poisson specifications also support this claim. Quite confidently, we can state that *complement* robustly predicts approximately 26% of the variance in officer appointments on vessels.[17] Secondly, a test does not exist to prove instrument exogeneity in exactly identified models as estimated here. We can claim, however, with a fair amount of statistical support that *complement* has no statistically significant effect on the number of engineers. Although it strongly correlates with the size of ships and the number of officers serving on ships, in repeated specifications (as shown in Appendix table A2), *complement* has no direct effect on the assignment of engineers to vessels.

Table 6 summarizes output from IV regressions and corresponding uncorrected estimates for comparison. Results from baseline (uncorrected) poisson regressions appear in column (1), while the semi-elasticities from an OLS regression that uses the natural log of engineers as the dependent variable appear in column (2). The IV problem is tackled using the three alternative strategies: the Mullahy (1997) GMM estimator (column (3)), a 2-stage quasi-maximum likelihood procedure (column (4)), and a two-stage least squares estimator (column (5)). Aside from the coefficient for *officers*, the core set of coefficients remain robust to IV corrections. In general, an increase in the number of officers on ships results in a corresponding increase in vessel needs for

[17] Results of various OLS first-stage specifications are reported in Appendix A1).

engineers.

The estimates reported so far in tables 3, 4 and 6 lead to several conclusions for the postbellum Navy. Newer, faster and bigger ships all required more engineers, but ships in need of constant repair and ships undergoing continual stress at sea also required large engineer staffs. Strong complementarities appear to also exist between officers and engineers. We explore this question with a slightly different measure in the next section.

Table 6: IV regressions of engineers serving on active vessels

| | QML | OLS | GMM | 2S-QML | 2SLS |
|---|---|---|---|---|---|
| | (poisson) | (linear) | (IV transformation) | (poisson) | (linear) |
| VARIABLES | (1) | (2) | (3) | (4) | (5) |
| age of vessel | -0.0396 | -0.0233 | -0.0837 | -0.0344 | -0.0151 |
| | (0.0257) | (0.0227) | (0.0604) | (0.0253) | (0.0023) |
| displacement (tons) | 0.0001*** | 0.0001*** | 0.0001*** | 0.00009*** | 0.0001*** |
| | (0.00003) | (0.00002) | (0.00003) | (0.00003) | (0.00002) |
| length (feet) | 0.0021** | 0.0014* | 0.0014 | 0.0020* | 0.0011 |
| | (0.0001) | (0.00008) | (0.0009) | (0.0010) | (0.0008) |
| cumulative sea | 0.0334*** | 0.0315*** | 0.0341*** | 0.0336*** | 0.0256*** |
| | (0.0118) | (0.0075) | (0.0106) | (0.0123) | (0.0081) |
| cumulative repair | 0.0349*** | 0.0443*** | 0.0377*** | 0.0336*** | 0.0444*** |
| | (0.0126) | (0.0091) | (0.0144) | (0.0125) | (0.0092) |
| **officers** | **0.0394***** | **0.0269***** | **0.0525*** | **0.0547** | **0.0768***** |
| | (0.0125) | (0.0094) | (0.0315) | (0.0362) | (0.0270) |
| observations | 563 | 549 | 563 | 563 | 549 |
| number of vessels | all specifications include the 87 vessels with data for ship *complement* | | | | |

Columns (1) & (2) included as baseline, not estimated with instrumental variables.
Columns (3) - (5) include *complement* as an identifying instruments.
Columns (4) and (5) use $\widehat{officers}$ as regressors estimated from linear first stage regressions.
For marginal effect comparisons, columns (2) & (5) use $ln(engineers)$ as the dependent variable.
All specifications include year (cohort) effects as well as age*cohort interactions.
Significance implied by *** p<0.01, ** p<0.05, * p<0.1. 2SQML standard errors not adjusted.

### 6.1.4 Engineer intensity and strong complementarity

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 *ratio* of engineers to officers on a ship. (Hence we estimate a relative measure for engineers.) Estimates from these regressions appear in columns (1) and (2) of table 7.

Consistent with the poisson regressions, we find consistent evidence for newer active vessels (those with higher $A_k$) and larger active vessels requiring a larger engineer to officer ratio. That is, there are *strong* capital-skill and technology-skill complementarities with engineers. Not surprisingly, ships with a history of requiring repairs also had larger ratios of engineers.

These results are echoed in figure 7, where vessels are split into two groups of characteristics: large versus small ships, fast versus slow ships, and old versus new ships. We subsequently chart the average share of engineers aboard each type for each year by each of these binary characteristics. For the 1890s (when the largest dispersion of old and new vessels steamed together), these diagrams indicate that larger engineer shares are associated with heavier, longer, newer and faster ships.

In contrast, figure 8 plots the average experience of engineers serving on vessels across time. By the 1890s the most "experienced" engineers served on lighter, shorter and slower ships. This is not surprising, since the most experienced engineers at this time included those without Naval Academy training, or without an understanding of the latest technologies. Larger, longer and faster ships needed younger, larger and more technically proficient cohorts of engineers.

We track these effects by measuring the experience levels of engineers at any point in time (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. Results from these FGLS estimated panel regressions are reported in columns (3) and (4) of table 7.

Vessels with larger displacements and longer service histories generate the most statistically robust results. An additional year of repair tends to decrease the experience of engineers serving aboard by approximately 2.5 months. At the same time, more experienced crews worked smaller ships, as suggested by negative coefficients on displacement. 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 7: Engineer intensity on active vessels

| | dependent variable | | | |
|---|---|---|---|---|
| | $\frac{engineers}{officers}$ | $\frac{engineers}{officers}$ | experience | experience |
| speed of vessel (knots) | -0.0148 | -0.1518*** | -0.1151 | 0.4611 |
| | (0.0148) | (0.0056) | (0.1075) | (0.4325) |
| speed-squared | - | 0.0056*** | - | -0.0208 |
| | | (0.0018) | | (0.0163) |
| age of vessel | -0.0206*** | -0.0366** | 0.0630 | -0.1976 |
| | (0.0059) | (0.0170) | (0.1937) | (0.2988) |
| age-squared | - | 0.0003 | - | 0.0049 |
| | | (0.0003) | | (0.0067) |
| displacement (tons) | 0.00005* | 0.0002** | -0.0007*** | 0.0003 |
| | (0.00002) | (0.00008) | (0.0002) | (0.0005) |
| displacement-squared | - | -8.3e-9* | - | -6.5e-8* |
| | | (5.0e-9) | | (3.6e-8) |
| length (feet) | 0.0019* | 0.0048* | 0.0055 | 0.0115 |
| | (0.0010) | (0.0027) | (0.0055) | (0.0099) |
| length-squared | - | -0.00001** | - | -0.00003 |
| | | (5.5e-6) | | (0.00004) |
| complement (sailors) | -0.0005* | -0.0015* | - | - |
| | (0.0003) | (0.0008) | | |
| complement-squared | - | 1.4e-6 | - | - |
| | | (1.0e-6) | | |
| cumulative sea | 0.0187** | 0.0296** | -0.1429 | -0.0951 |
| | (0.0079) | (0.0126) | (0.1096) | (0.2006) |
| cumulative sea-squared | - | -0.0002 | - | -0.0019 |
| | | (0.0003) | | (0.0085) |
| cumulative repair | 0.0110** | 0.0086 | -0.2170* | -0.3953** |
| | (0.0056) | (0.0171) | (0.1309) | (0.1957) |
| cumulative repair-squared | - | 0.0002 | - | 0.0084 |
| | | (0.0008) | | (0.0119) |
| officers | - | - | 0.0547 | 0.3717* |
| | | | (0.0892) | (0.1967) |
| officers-squared | - | - | - | -0.0270** |
| | | | | (0.0112) |
| constant | 0.1511 | 0.8615** | 21.69*** | 18.303*** |
| | (0.1905) | (0.4355) | (2.7999) | (3.9365) |
| observations | 501 | 501 | 633 | 633 |
| number of vessels | 80 | 80 | 103 | 103 |
| overall $R^2$ | 0.3070 | 0.3659 | 0.5588 | 0.5729 |
| $\chi^2$ test of age*cohort interactions | 294*** | 288*** | 124*** | 204 |
| Breusch-Pagan lagrange multiplier | 21.99*** | 6.35** | 5.39** | 1.88 |

Random effects included for all regressions (FGLS)

Bootstrap standard errors shown in parentheses, with *** p<0.01, ** p<0.05, * p<0.1.

All specifications include year and age*cohort interactions.

## 6.2 Maintenance & Installation - vessels in construction and repair

To examine labor complementarity in the maintenance and installation of naval vessels, we match those vessels in navy yards with the numbers of engineers assigned to those yards. For each navy yard with ships under construction or repair, we construct annual measures of the average age of these ships, average displacement, average length, and average speed. We control for general shipyard activity with a proxy based on employed "civil engineers" in a yard.[18] That is, bigger and more active shipyards would presumably require more civil engineers for general harbor maintenance. This proxy therefore serves as a control for general time-varying shipyard capacity constraints. We cannot directly match skilled labor to individual vessels, since personnel working in navy yards likely performed a wide range of jobs, only some of which involved the construction or repair of docked vessels. Estimates, therefore, may not directly relate to operational demands for engineers on ships under repair. Also engineer demands in a shipyard depend on the number of ships under repair, essentially defining our variable of interest as a labor-capital ratio, $\left(\frac{engineers_{it}}{shipcount_{it}}\right)$. To address fluctuations in demand based on the preponderance (or lack thereof) of ships docked in a shipyard, we control for the probability of exposure in the poisson regressions using $shipcount_{it}$ as an offset variable. This implies a baseline specification defined as a rate of engineers per number of ships within a specific yard.

The results that appear in table 8 produce interesting estimates regarding labor complementarities in vessel maintenance. Most notably, the association between officers, civil engineers and engineers remains positive and consistent in size across specifications. The result indicating officer complementarity does not surprise, since we already established anecdotal and empirical complementarity between officers and engineers in our earlier study of ships at sea. The second result regarding civil engineers appears to be somewhat of a surprise, but also indicates that naval and civil engineers shared complementary roles. That is, civil engineers and naval engineers were *not* substitutes in ship maintenance.[19]

Ship age also has a positive role on the size of engineer crews. Consistent with shipyard trends demonstrated in figures 6 and 7, evidence given in column (1) of table 8 suggests that the Navy

[18]Like other data used in this study, we gather information on civil engineers from annual *Navy Registers*.

[19]We also have the number of naval constructors in each yard as an additional potential skilled-labor group, but find no statistically significant relations between the number of constructors and engineers in a shipyard.

pulled engineers away from ship duty and back into shipyards during the 1890s. Additional evidence indicates that this trend is actually an artifact of the age of ships under maintenance and installation. Strikingly, brand new vessels (those under construction) do not appear to require more engineers (or naval constructors) than their world-weary repairing counterparts. All considered, more technologically advanced vessels (as proxied by age) appear to require *fewer* engineers for construction and repair. This result appears consistent with our suggested results from section 3. Finally, the results shown in columns (3)-(6) indicate that factors related to mass and speed (another proxy for technology) do not impact demand for engineer labor assigned to ship maintenance and repair.

Table 8: Poisson regressions of number of engineers assigned to navy yards on repairing vessel characteristics

| VARIABLES | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| average age | – | 0.0164*** | 0.0203*** | 0.0119 | 0.0178* | 0.0062 |
| | | (0.0037) | (0.0070) | (0.0078) | (0.0106) | (0.0096) |
| average speed (knots) | – | – | -0.0161 | -0.0304 | -0.0238 | -0.0513 |
| | | | (0.0908) | (0.0286) | (0.0833) | (0.0394) |
| average displacement (tons) | – | – | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| | | | (0.0001) | (0.0001) | (0.0001) | (0.0001) |
| average length (feet) | – | – | -0.0006 | 0.0008 | -0.0006 | 0.0012 |
| | | | (0.0054) | (0.0024) | (0.0043) | (0.0025) |
| officers | 0.0583*** | 0.0622* | 0.0637 | 0.0693*** | 0.0618* | 0.0725*** |
| | (0.0208) | (0.0359) | (0.0425) | (0.0163) | (0.0360) | (0.0195) |
| civil engineers | 0.1497*** | 0.1662** | 0.1165 | 0.1312*** | 0.1114 | 0.1175** |
| | (0.0536) | (0.0789) | (0.0916) | (0.0466) | (0.1198) | (0.0586) |
| years 1880-1889 | 0.0832 | – | – | – | 0.0230 | 0.1135 |
| | (0.1014) | | | | (0.1426) | (0.1419) |
| years 1890-1899 | 0.2903*** | – | – | – | 0.1068 | 0.2074 |
| | (0.1082) | | | | (0.2633) | (0.2113) |
| observations | 150 | 150 | 142 | 142 | 142 | 142 |
| number of navy yards | 8 | 8 | 8 | 8 | 8 | |
| pseudo $R^2$ | – | – | – | 0.120 | – | 0.123 |
| yard fixed effects | yes | yes | yes | no | yes | no |

Yard-specific ship counts included in all regressions as exposure offset variables.
Bootstrap standard errors shown in parentheses, with *** p<0.01, ** p<0.05, * p<0.1.

# 7 Conclusion

As the nation proceeded through the second industrial revolution, 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 construction and repair. We also observe relatively fewer *worker*-skill complementarities with engineers than with officers. Officers retained their comparative advantage in managing the complement of sailors. Skilled workers were highly specialized, and the late-19th century Navy was one where complementarities abounded.[20]

The implication that newer and possibly more technologically advanced vessels required fewer skilled technicians for maintenance and installation complicates the history of technology-skill complementarity. Contrary to the Goldin-Katz study that deals with factory-oriented manufacturing (where production can be considered a fairly straight-forward process of assemblage), the Navy was an industry in which newer and more advanced "high-technology capital" was difficult to operate but fairly straight-forward to build and 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 complicated machinery on ships and aircraft, but low-skill personnel (enlisted sailors) are charged with the occupations of day-to-day maintenance. If other technologically-oriented manufacturing and service industries were structured similarly, the story of the development of capital and technology-skill complementarities may require some revision.

[20] 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).

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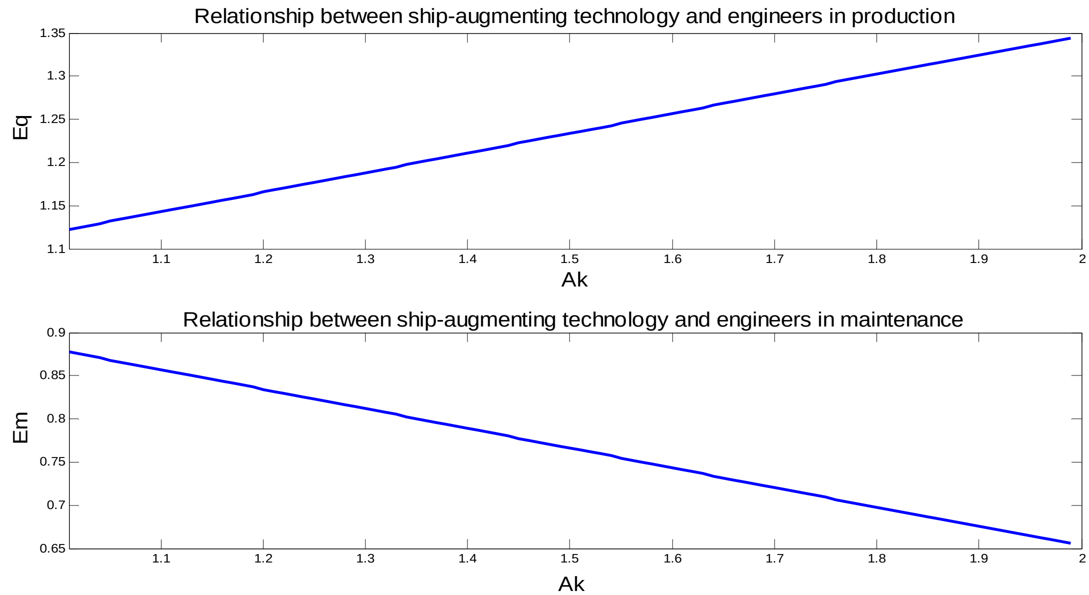
Figure 1: Numerical simulations of optimal allocation of engineers with changes in capital-augmenting technology

**ρ = -10**




**ρ = 0.5**

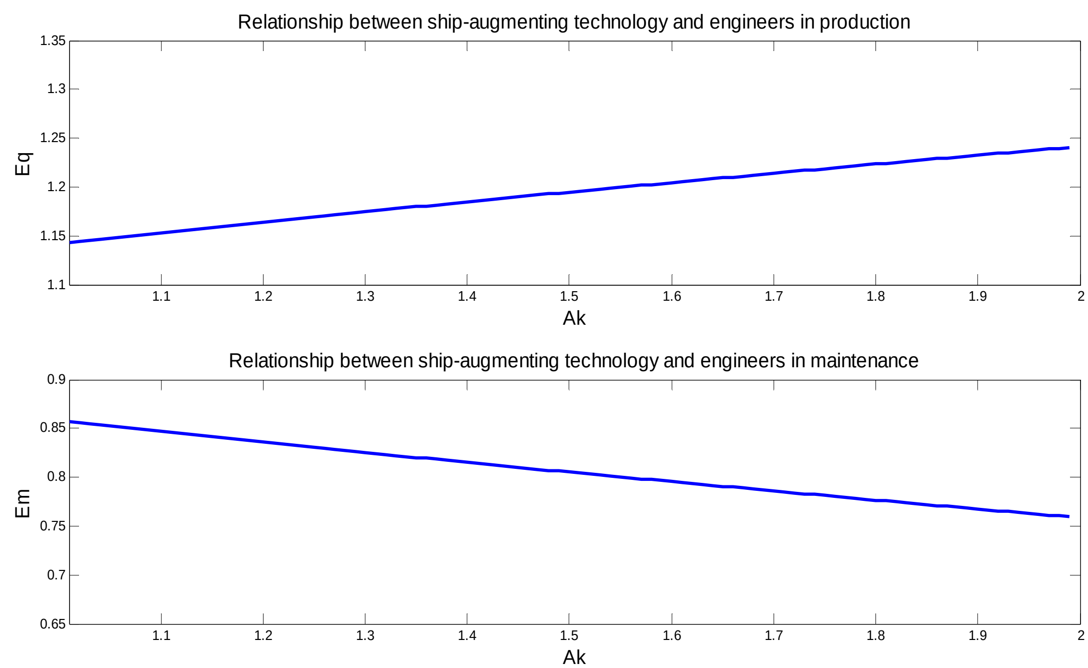


Figure 2: Numerical simulations of optimal allocation of engineers with changes in substitutability between capital and labor in production

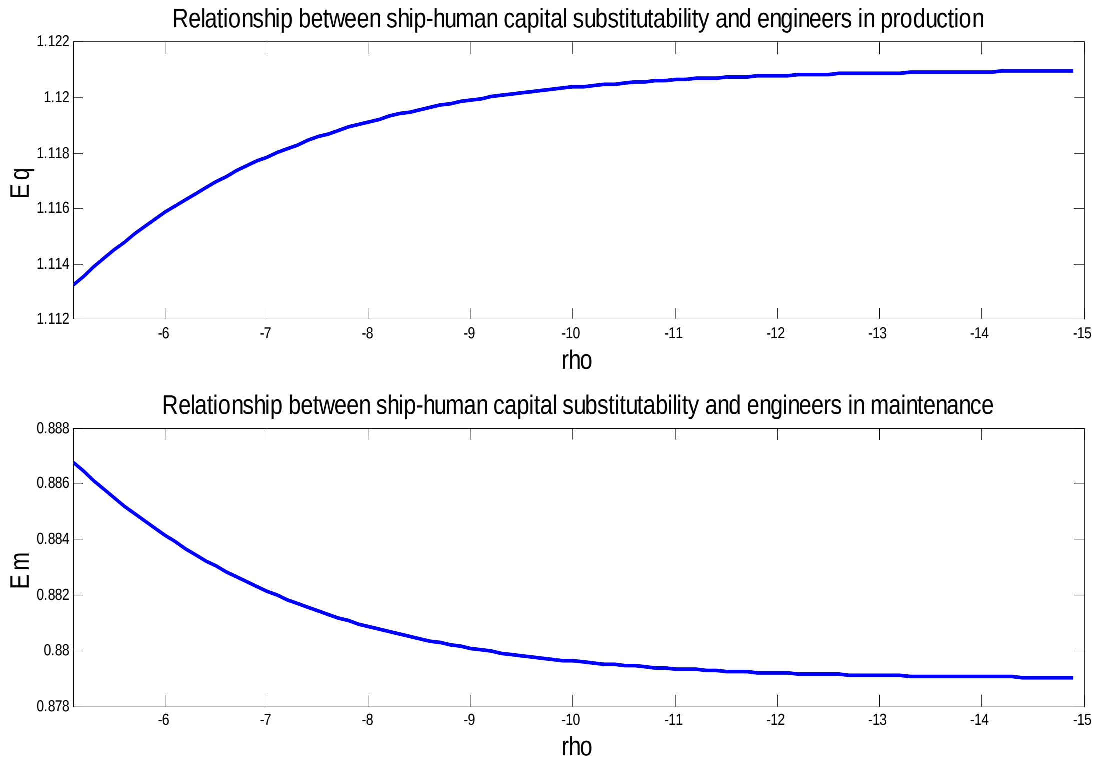
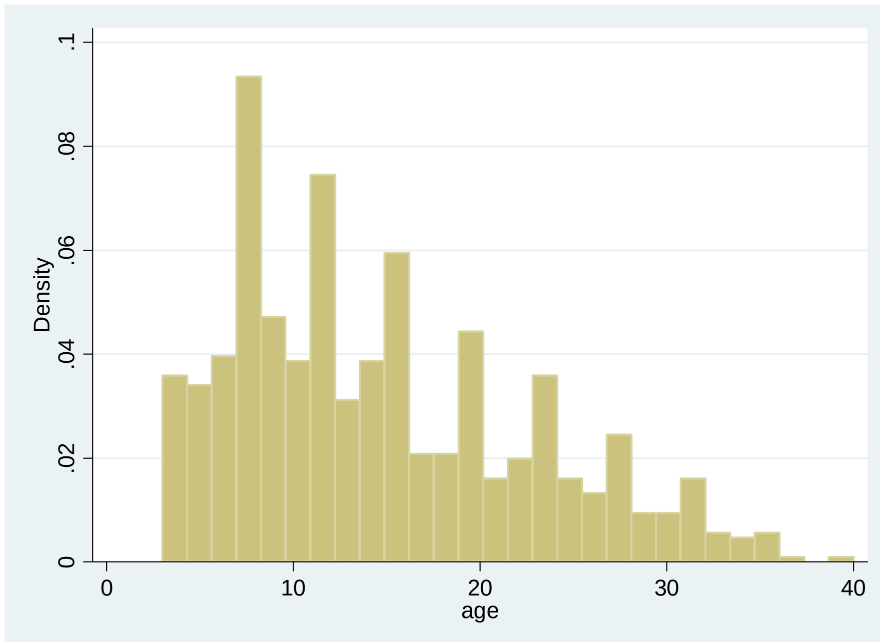


Figure 3: Age profiles of naval vessels

Age of all active vessels across all years




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

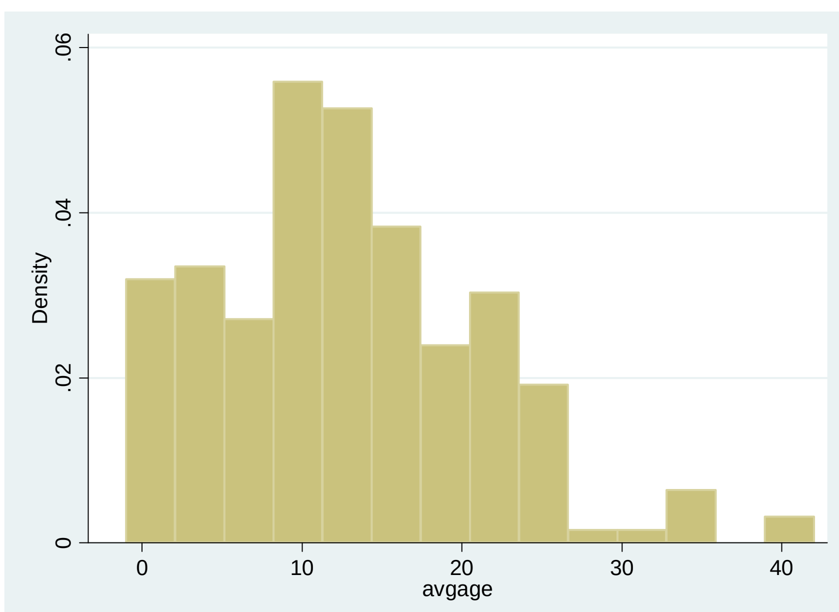
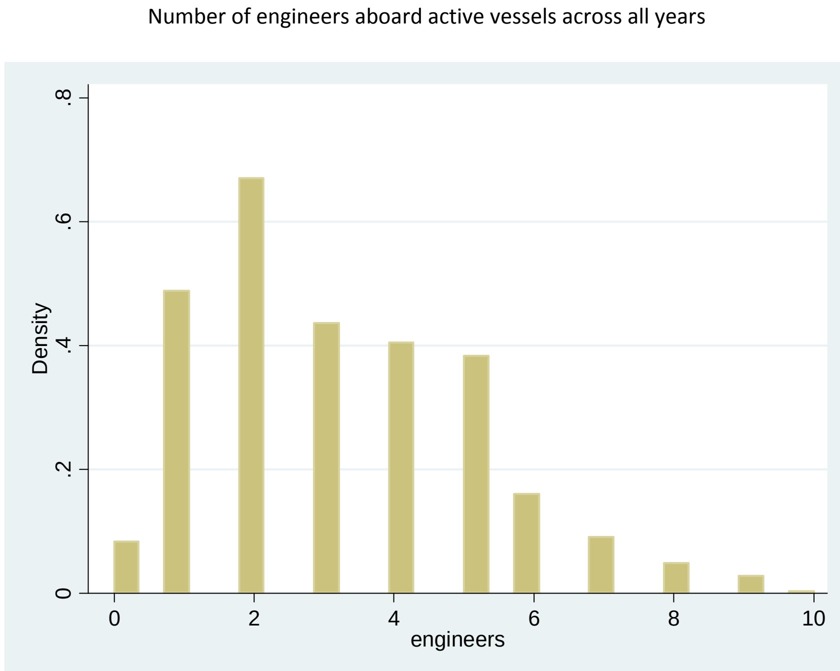


Figure 4: Numbers of skilled labor on active vessels



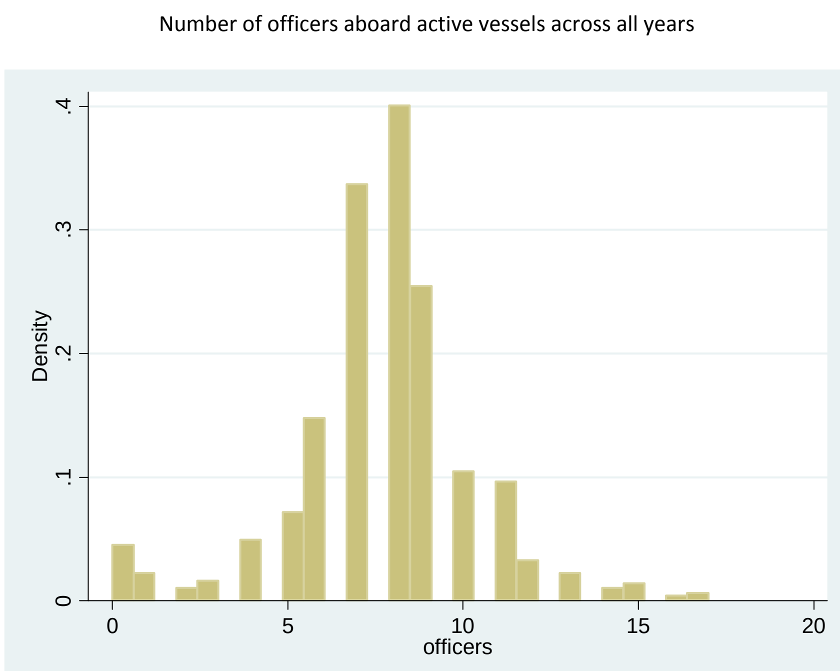



Figure 5: Vintage effects over time

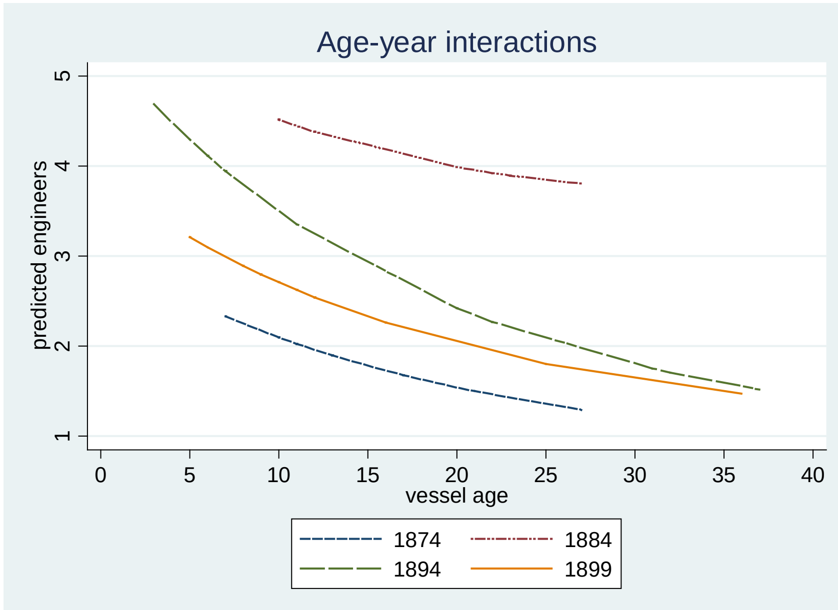


Figure 6: Ship use and labor demand

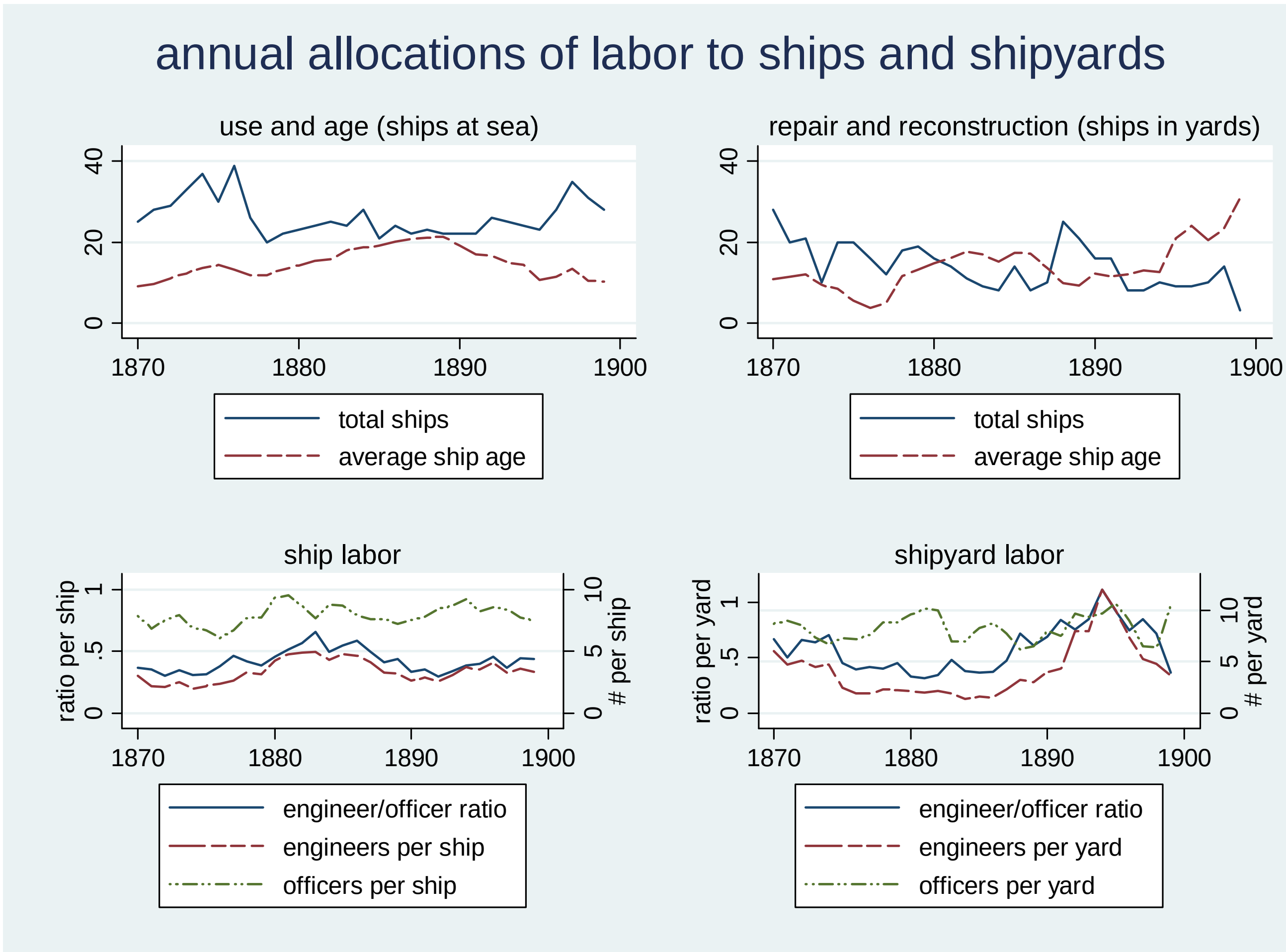


Figure 7: Share of engineers (relative to all skilled personnel) on active vessels, year by year

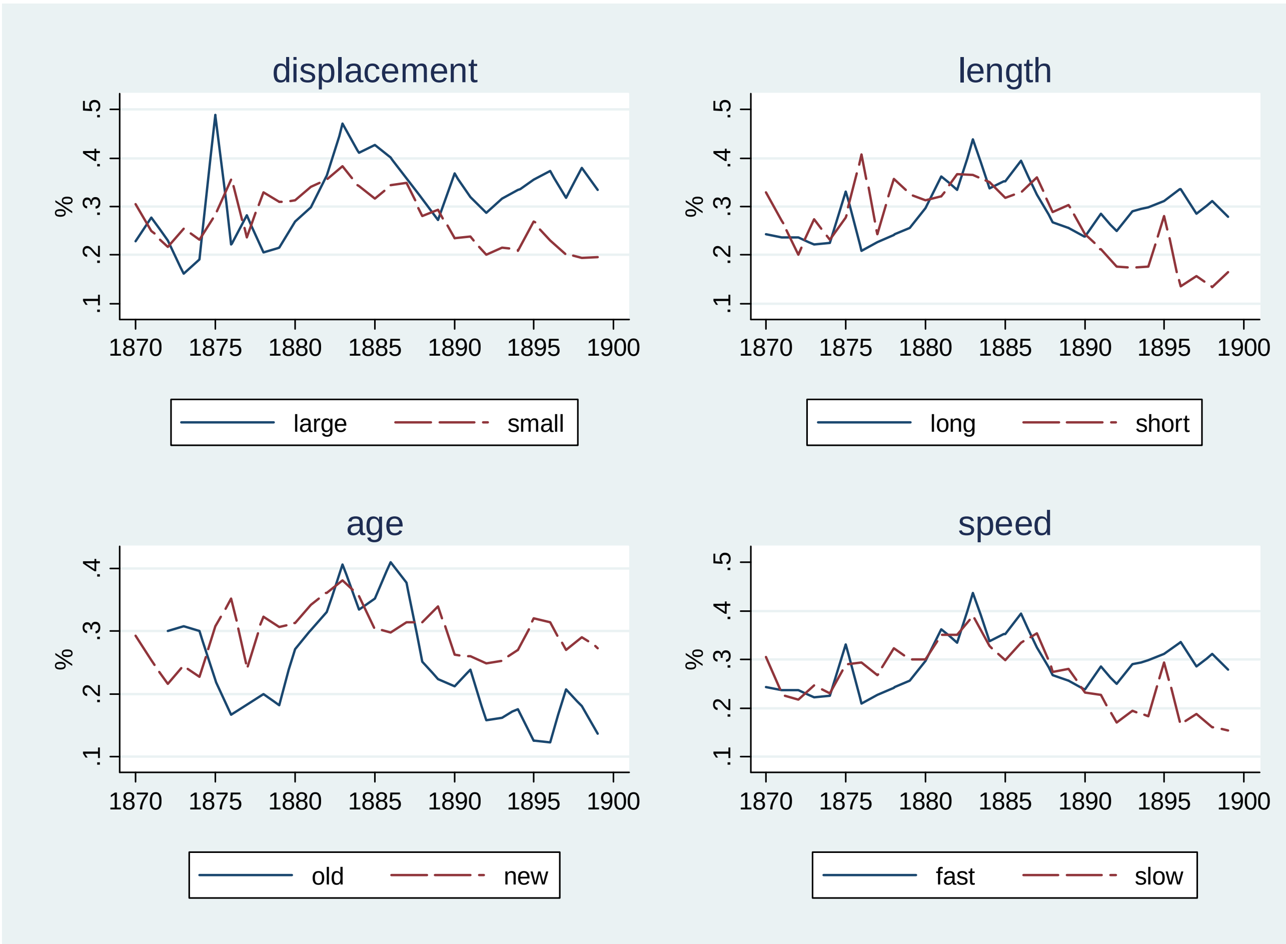
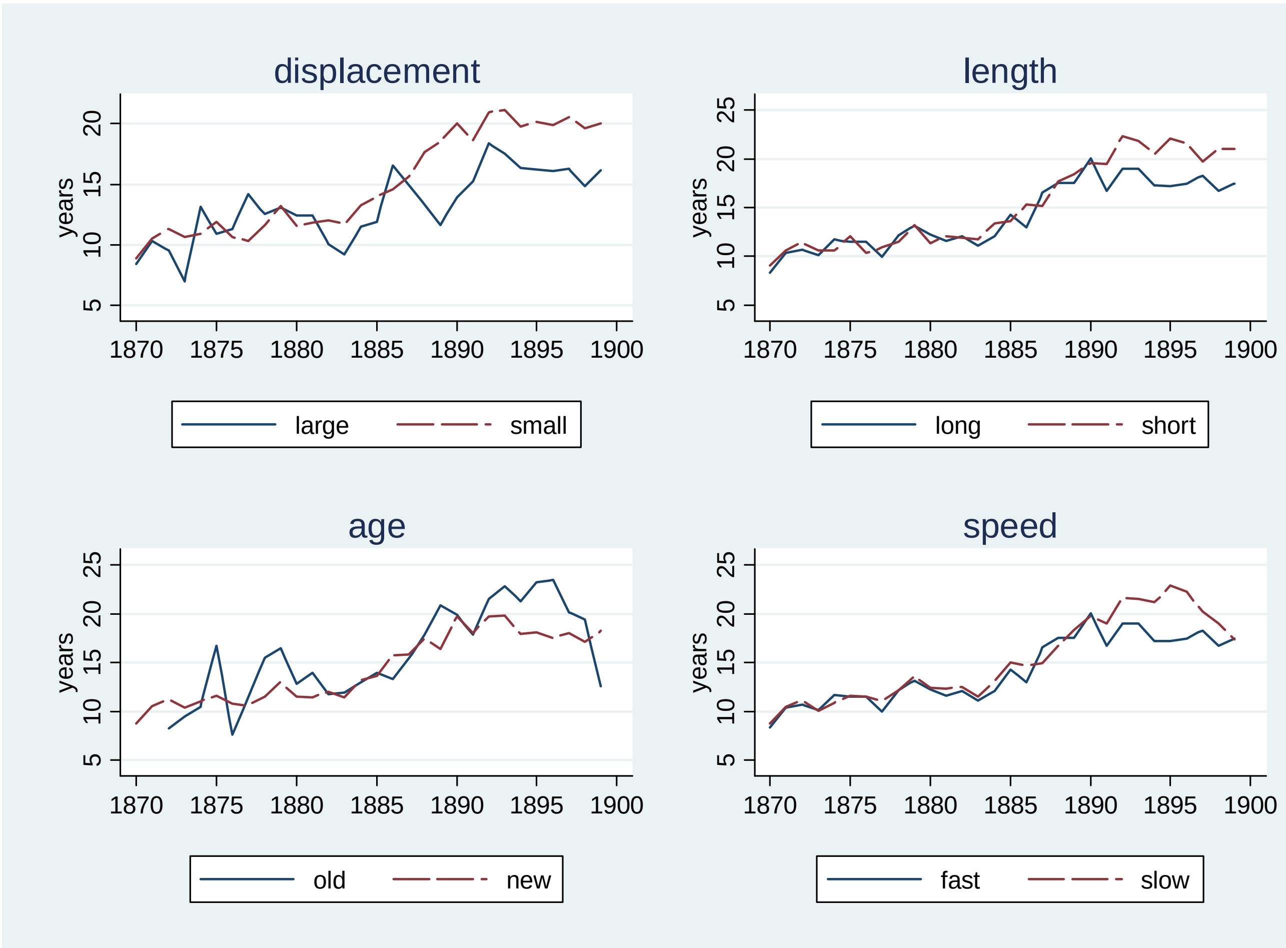


Figure 8: Experience of engineers on active vessels, year by year



# 9 Appendix

Table A1: First-Stage OLS for *Officers* (used in IV regressions)

| | (1) | (2) | (3) |
|---|---|---|---|
| complement | 0.0104*** | 0.0107*** | 0.0108*** |
| | (0.0013) | (0.0008) | (0.0008) |
| age of vessel | -0.0720 | - | - |
| | (0.0676) | | |
| displacement (tons) | -0.00002 | - | - |
| | (0.0001) | | |
| length (feet) | 0.0011 | - | - |
| | (0.0036) | | |
| cumulative sea | 0.0763** | - | - |
| | (0.0341) | | |
| cumulative repair | 0.0652 | - | - |
| | (0.0396) | | |
| observations | 563 | includes only observations with *complement* data | |
| number of vessels | 87 | | |
| $\chi$-squared test of age*cohort interactions | 0.82 | 1.10 | - |
| $R^2$ | 0.4374 | 0.4324 | 0.2636 |
| Model fit F-stat | 6.63 | 6.53 | 210.9 |

Columns (1)-(4) include year effects as well as age*cohort interactions.
Significance implied by *** p<0.01, ** p<0.05, * p<0.1.

Table A2: (Lack of ) effect for *Complement* on *Engineers*

| VARIABLES | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| complement | 0.0005 | 0.0006** | 0.0002 | 0.0002 | 0.00008 | 0.0008 |
| | (0.0003) | (0.0003) | (0.0004) | (0.0004) | (0.0005) | (0.00008) |
| complement-squared | - | - | - | - | - | -1.7e-6 |
| | | | | | | (1.3e-6) |
| observations | 563 | includes only observations with ship *complement* data | | | | |
| number of vessels | 87 | | | | | |

each column represents same specification as table 3 with addition of *complement* regressor(s)
other coefficients not reported
standard errors in parentheses, bootstrap estimators except in random effects specifications
*** p<0.01, ** p<0.05, * p<0.1