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THESIS

**LONG-TERM IMPACT OF PERSONNEL VACANCIES
IN A MULTI-CREWING CONCEPT
(MCC)—MODELING AND SIMULATION**

by

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March 2019

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MULTI-CREWING CONCEPT (MCC)—MODELING AND SIMULATION**

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ABSTRACT

Modern navies face a highly competitive labor market, particularly in technical and medical specialties. Among other issues, long deployment times contribute to difficulties in recruiting, resulting in vacancies and shortfalls in manning on board seagoing units. Another challenge worldwide navies face is the reduced availability of platforms. Multi-crewing concepts offer a way to increase efficient use of the scarce platforms. These concepts generally separate crews from ships as independent elements that require specific scheduling. The present study finds that previously introduced scheduling optimizations for personnel and ships do not consider permanent and temporary personnel shortfalls. The study assumes that a certain vacancy rate will lead to an increased level of interchangeability within crews that may reduce force readiness or result in the collapse of the crewing system. In this thesis I create a generic crewing model and simulate different vacancy states to analyze their impact on crew composition. The model incorporates a constraint of maximum absences for each individual in the crews, focusing on the resulting increase in personnel turnover and number of unmanned billets. It finds that the vacancy rate exponentially affects the resulting number of unmanned billets and increases the additional turnover rate, which has a negative effect on a crew's performance.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAW	Anti-Air Warfare
ASW	Anti-Submarine Warfare
ASuW	Anti-Surface Warfare
BIBB	<i>Bundesinstitut für Berufsbildung</i> (Federal Institute for Vocational Training)
BMVg	<i>Bundesministerium der Verteidigung</i> (Federal Ministry of Defense)
CBM	Crews, Boats, Missions
COP	Combined Operations Plan
DESTATIS	Statistisches Bundesamt
EliTMaat	<i>Elektrotechnikmaat</i> (Electro Technical Petty Officer)
FAS	Fleet Activity Schedule
IUC	Intensive Use Concept
LAT	Leave and Training Plan
MBM	<i>Mehrbesatzungsmodell</i> (Multi-Crew Model)
MCC	Multi-Crewing Concept
MTC	Mission Training Center
OLS	Ordinary Least Square
OTC	Operational Training Center
RAN	Royal Australian Navy
SchiffsBetrTMaat	<i>Schiffsbetriebstechnikmaat</i> (Ships Technical Petty Officer)
SchiffsTOffz	<i>Schiffstechnikoffizier</i> (Ships Technical Officer)
SchiffsTStOffz	<i>Schiffstechnikstabsoffizier</i> (Ships Technical Staff Officer - Chief Engineer)
SD	Standard Deviation
TA	Temporary Absence
TL	Turnover Loss
VBA	Visual Basic
VR	Vacancy Rate

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EXECUTIVE SUMMARY

This thesis uses a linear optimization model to conduct a simulation of the personnel movement and assignment process to verify the sustainability of a multi-crew concept (MCC). This verification targets the number of unmanned billets and personnel turnover-rate during deployments of single crews in relation to a vacancy rate in the whole crewing system.

In times of scarce resources and a constantly high level of deployment, for different navies MCCs represent an opportunity to utilize existing resources more economically. These crewing models rely on the administrative separation of the crews from the ships. There are various alternatives to determine numerical ratio of ships and crews; different requirements in forward presence and the operational availability require different approaches of MCCs. One option presented is a rotation concept in which a number of crews are deployed on a smaller number of vessels. The recently introduced German frigate class F125, for example, uses eight crews to constantly man and deploy four units. Depending on its construction and its capability, the ship remains in the operational area for a long period (high intense use), while the crews regularly rotate at concise periods. The goal of these attempts is to utilize the resources more effectively (e.g., by avoiding the transit time the ship needs to reach the area of operation). A high degree of individual specialization characterizes the MCC and the low manning design of modern ships in general. This reduces the interchangeability of individuals, and thus, the flexibility of the entire model.

Planning requires an independent but coordinated scheduling process for these two elements: ships and crews. There are many existing models optimizing the scheduling of crew and ships. None of the reviewed models respects potential shortfalls in overall crewing. Each of them presupposes fully manned crews. A high level of automation and coherent specialization of an individual's skills leads to a decreased tolerance for unmanned billets during a ship's deployment because on-board redundancies for replacement are limited. Personnel planners need to fill frequently occurring, acute vacancies in crews with personnel from other crews. The available personnel resources are

reduced if the possibility of replacement is reduced by the limitation of the individual's absence per period: The more time a sailor is available, the greater are the replacement options. The limitation of absence could also be considered for recruiting in terms of increasing the predictability and reducing the time of absence.

Literature suggests that a high personnel turnover rate has an impact on the overall team performance if the turnover is not intended. The lower performance may result from increased loss of experience and knowledge in a crew, a reduced flow of tacit knowledge due to changing crew composition, and the change of flux. Flux is the team's ability to convert inputs to outcomes via variation in coordination mechanisms.

Using a stylized schedule of deployment and a model crew derived from the manning of the technical department of a F125 frigate, I simulate a one-year cycle of seafaring and manning assignments. The simulations and the model solution indicate that a linear increase of the overall vacancy rate causes an exponential increase in unmanned billets during deployment across all crews. Further, the turnover rate increases until the point where there are too few personnel to create sufficient redundancy. Based on literature about turnover in teams and related outcomes in team performance, I conclude that there is a negative effect of vacancy-caused turnover on a crew's performance. In an operational and potentially dangerous environment, this may cause severe risk to the safety and the lethality of a warship's output. The simulation also shows that the vacancy rate in the crucial times of scheduled deployments can be of great concern and needs to be included in the planning process.

From my findings I derive recommendations to increase the organizational structure and thereby create more personnel redundancies. I further recommend adjusting constraints on the number of permitted absences for individuals based on their specialization. Further, modifying deployment schedules according to requirements in times of reduced availability of personnel could minimize clusters. The underlying Microsoft Excel-based simulator can be used by the planning authorities during the planning process to improve the planning process.

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I. INTRODUCTION AND BACKGROUND

Personnel and platforms reflect finite resources in worldwide navies. The availability of units in Western countries has declined noticeably in recent years (Mannhardt, 2016), while the load on operations remains on a high level. For the German Navy, this was a decrease from 224 units in 1992 to 75 units in 2005 (Stockfisch, 2012). The present target structure of the German Navy is 55 units. To sustain a high level of deployments in areas of operation all over the world, the average sailor has to cover a higher load. This has a negative effect on the number of capable applicants, which aggravates the problem of personnel availability and individual deployment time (Federal Ministry of Defense [BMVg], 2016). Furthermore, the low unemployment rate correlates with a strong economy (Maier et al., 2018), and the overall attractiveness of the service on board negatively affects the recruitment of the armed forces in general. Especially in technical billets, the German Navy and the German Armed Forces (*Bundeswehr*), as a whole, face reasonable vacancies (BMVg, 2016).

With the F125 class frigate (F125) the German Navy introduces a multi-crew concept (MCC), an Intensive Use Concept (IUC) of the ships, and Mission Training Centers (MTC) ashore. For the first time for the German Navy, both platform and crew will be separated consistently. By shifting sections of training ashore, ships are available for missions simultaneously. These measures should lead the focus of the crews to missions and deployments. The purpose of this concept is to increase the “arithmetical” availability of operational-ready units (Krause, 2015). This means to minimize the usual transit times to the areas of operation and to optimize the operational utilization of the ships and crews. In terms of attractiveness of service, the individual absence time per sailor should be limited. Crews will be deployed as teams on a rotation basis on the available platforms. The crews’ handover will occur in the areas of operation.

Beside other unknown effects of the MCC on motivation or training standards, a very important consequence is the impact of personnel interchange on sustainability and operational readiness in terms of manning.

Increasing automation and the concomitant reduction in crew strength is leading to a generally increased specialization of the crew members (Powers, 2016; Wood, 2014). To a certain extent, this reduces the possibility of balancing vacancies crew-internally. The German Navy, like other branches, faces a highly competitive labor market, especially in technical and medical professions. Additionally, recruitment procedures and restrictions lead to difficulties in recruiting (*Personalstrategie der Bundeswehr*; BMVg, 2016). The consequences are vacancies within the crews. These vacancies need to be compensated by substituting identically trained officers and sailors from other crews.

According to the *Personalstrategie der Bundeswehr* (BMVg, 2016), challenges consist of demographic, societal, technical, and organizational factors. Based on 2014 data, the working force, consisting of people aged 15 to 66, is expected to diminish by eight percent until 2030. Social diversity and change will result in different life plans and changed expectations of potential applicants to the armed forces. In the broader society higher education levels typically leads to fewer traditional apprenticeships, especially in technical professions. Moreover, increased individualization has effects on leadership; the increasing usage of social media also has a vast impact on communication, social interaction, and organizational cultures. Further, technical developments like digitalization and automation require more specialized experts in all areas of professional life and therefore also in the Navy.

In 2011 the Bundeswehr suspended the compulsory military service, and this had an impact on the recruitment for voluntary time contracts and professional employment in the German military (BMVg, 2016). The attachment to public administration employment and contracting leads to an inflexible personnel body. As a result of these changes, the Bundeswehr comprises an aging force from which many experienced soldiers will be leaving in the coming years, and fewer similarly skilled young soldiers will be available to replace them. Personnel bottlenecks in the military field result in the reduced availability of specialists in different ranks, especially in technical and information technology professions, as well as in medical service (BMVg, 2016).

Consistent with the report of the Military Commissioner of the *Deutscher Bundestag* from 2017 naval electronic non-commissioned officers (NCO) only have a

placement rate of 45 percent; that year 120 of 267 billets were filled (Bartels, 2018). The *Bundeswehr-Journal* in 2016 stated as examples that the rates of Electrical Engineering and IT-System-Support personnel are undermanned by at least one third: “In the Navy, there is a significant shortage of personnel in the positions of “electrical engineering” (target: 687 / actual: around 400), “marine electronics” (target: 644 / actual: about 450) and “IT system support” (target: 638 / actual: around 400) (Dewitz, 2016).

As early as 2011, the Federal Court of Auditors explicitly criticized the multi-crew models of the German Navy. The court stated that the goal of reducing the individual absence from 180 days per year per sailor to 120 days would lead to higher personnel needs and additional costs, without reducing the resulting temporal load. Especially for frigates, where the average training time for operational readiness is up to 100 days per crew, the court assessed it unrealistic to hold these goals (Engels, 2012).

A. PURPOSE

In order to maintain the ability of three-dimensional warfare on a ship, the coordinated interaction of various actors is of the utmost importance. The areas of internal and external battle (with their components of the classic warfare areas like anti-aircraft warfare [AAW], anti-submarine warfare [ASW], and anti-surface warfare [ASuW]) require a significant coordination effort within the crew, which I consider as a team. Not only in combat, but also in peacetimes, be it seafaring, training, or administration, a high degree of coordination is required to maintain the safety of crew and ship on a high-performance level. The implementation of MCCs is rattling the common integrity of ship and crew.

The purpose of this thesis is to validate an MCC by simulating permanent and unexpected temporary vacancies in manning. The simulation tests the functionality and robustness of the MCC. Primary outputs of the simulation and modeling process are the total turnover during deployment for each crew, and the number of unmanned billets resulting from vacancies. The total turnover is each personnel movement within the crew, where the individual assigned to a billet changes from sub-period to sub-period. I assess a billet as unmanned if no individual—also in the context of replacement from other crews—

can be assigned to an assignment on board. The total turnover rate and the number of unmanned billets work as a basis for assessing the impact on team performance on board a ship. I determine a degree of vacancies when the fulfillment of tasks is no longer possible at an optimum assignment and find critical values for different departments and specializations.

Research Questions:

I divide my research question into a primary and two secondary questions.

Primary Question

- How can vacancies affect the crew composition, personnel readiness, and team performance of an MCC?

Secondary Questions

- At what percentage of overall personnel availability will the MCC fail?
- Are there differences in specializations for sustainable manning?

I assume that personnel shortages and the following replacements will have massive impact on crew composition or will result in performance losses and finally failure of the MCC.

B. SCOPE AND METHODOLOGY

With the developed model, I simulate different manning and deployment states and create “generated experiences” and synthetic data in multi-crew manning. The simulations and the resulting crew assignments (conducted with a linear optimization model) show all movements in crew composition.

The scope of this thesis includes:

1. The definition of objective function, constraints, and variables—Chapter IV.

2. The development of a model for linear optimization of personnel shortfalls under the conditions just identified in item 1.
3. The conduct of time-discrete simulation and optimization to consider the impact of vacancies on the future composition of crews.
4. A calculation of the total turnover and number of unmanned billets.
5. The discovery of the critical vacancy rate, where individual time constraints (e.g., ≤ 120 days at sea per individual) cannot be met.

For this thesis, I conduct the following steps:

- Perform a literature review of books, magazine and scholarly articles, and other library information resources on the multi-crew concept, critical embarkation rates, and other related topics—Chapter II.
- Review the literature on the effects of replacing individuals on group efficiency in order to define a limit for inter-crew exchange and personnel replacement—Chapter II.
- Include a brief review of the history and types of MCCs, purpose, and the motivation behind their implementation—Chapter II.
- Create a model for linear optimization of vacancy management—Chapter III.
- Build a simulator and solver to create the personnel turnover and absences throughout a period of time. For this task, I use Microsoft Excel 365/ Visual Basic (VBA) and the standard available solver—Chapter III.
- Define time periods according to a generic deployment schedule for the crews—Chapter IV.
- Conduct, record, and analyze simulations—Chapter IV.
- Optimize and record crew assignments—Chapter IV.

- Record and analyze the collected data—Chapter V.
- Propose recommendations for improvement of MCC and discuss implementation of alternative concepts—Chapters VI and VII.

C. CAPABILITIES AND LIMITATIONS OF THE MODEL

The results relevant to my research are the turnover resulting from the personnel movements necessary to compensate personnel from unit to unit and the unmanned billets resulting from failed compensation. To get these results, I create a model that bases on components from the MCC for the German F125 frigates. These components are used as a basis for the model creation and evaluation but can be replaced by any required MCC approach. that simulates a one-year deployment cycle. The basic variables for this model are the general vacancy rates, short-term personnel shortages, and losses due to regular personnel turnover. The losses from personnel turnover arise from the overlapping of incoming and outgoing individuals. Based on a crew deployment schedule that can be entered and changed manually, and a changeable personnel structure, the model simulates the required personnel movements within the system to man operational crews. Here, a one-to-one substitution is required: All competences of a billet can be replaced only by equivalent staffing from other crews.

The model is divided into two steps. The first step allocates personnel for the entire period in order to obtain a future-oriented optimization. In the second step acute vacancies that either were not covered in the first step or arise due to temporary absences are compensated for in each sub-period. Both steps differ primarily by the length of the observation period. The allocation process itself is not significantly different. For this, the personnel demand (vacancies for crews that are deployed) and the personnel supply (manned billets with remaining working time in undeployed crews) are filtered. The allocation of personnel supply and demand then only takes place on the basis of the individual absence. While in the first step individuals with little or no absences are assigned to vacancies, in the second step individual absences are maximized up to the specified maximum individual absence. This keeps the number of movements from ship to ship to the minimum required.

The result of the allocation process is the direct assignment of an individual to a billet in another crew. This assignment follows—according to the linear model—exclusively on the basis of the calculated individual absence. Other aspects that could be of relevance for an assignment to another crew, such as experience, second or third skills, level of training, or the like—since they are sometimes very subjective to evaluate—are disregarded. Furthermore, in the optimization process a 100-percent occupation rate is always required as a goal, since the acceptance of vacancies should also be on the subjective assessment of the commanding officers (CO) or their superior departments. This assessment is not part of this work. The resulting crewing lists are therefore not to be seen as an absolute solution for the allocation of personnel, but rather to give an overview of the expected turnover and the expected vacant positions to provide a statement about the persistence of a multi-crew concept. On the basis of scientific papers on the subject of turnover and performance and the resulting defects, I make an evaluation of the results.

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II. LITERATURE REVIEW

The literature review on multi-crewing reveals that during years 2006 to 2008 many Western navies were introducing and analyzing MCCs and optimization of scheduling for crews and platforms.

A. THE MULTI-CREWING CONCEPT IN THE GERMAN NAVY

The MCC F125 was implemented to increase operational availability with a lower number of platforms, aimed at increasing the attractiveness of seagoing billets by reducing the load for the individual and by enhancing the predictability of sea billets. At the same time, as the utilization of platforms increases, the goal is the diversification between platform and crew to allow more efficient use over longer periods. With a handover of the ships in the area of operation, operational availability increases almost by the same amount of time the platform would have been used for transit prior to the implementation.

1. Concept

The German Navy employs MCCs on various types and platforms. Table 1 provides an overview on the MCCs for each platform:

Table 1. Multi-crewing in the German Navy.

Class	Platforms	Number of Crews	TLC ¹
U 212 Submarine	6	7	1
K 130 Corvette	5	5	2
MJ 332 MCM	8	9	2
FD Boot 423 Auxiliary	3	4	-
F 123	4	5 ²	1 (3 Teams)
F 124	3	42	
F 125	4	8	
EGV 702 Auxiliary	3	42	

¹ Technical Logistic Component

² The additional crew has less manning than the standard crews.

In particular, the seagoing units of the “*Einsatzflottille 1*” that consists of smaller units use MCCs in different forms. The MCCs of the “*Einsatzflottille 2*” (frigates and auxiliaries) for F123, F124, and EGV 702 have an additional crew, which differs in size and organization from a standard crew. Although individuals from these additional crews can be replaced on single occasions, the crew or a department cannot be replaced in its entirety.

The F125 class frigate is the first German Navy seagoing unit; consequently developed for long-term and multi-crew deployments. The concept includes the platforms and crews as well as organizational and infrastructural elements required to run the MCC and optimize the available time of deployment.

Generally, this MCC is a modular and specific system consisting of the following elements:

- Crews with a class-specific number of individuals,
- Technical-logistic components (TLC),
- Sea- and shore-based operational training (Operational Training Centers, OTC),
- Reserve for unplanned vacancies (crew reserve), and
- Resulting staff and leadership structure (staff).

In order to be successful, the coordinated deployment of all those elements is essential. The crews are deployed alternately on the operational platforms. TLCs are in charge of the non-operational units during their shipyard stay to relieve the operational crews for recreation from deployments, operational training, and preparation for future deployments.

Operational platforms remain in the area of operation while deployed crews can be exchanged with fresh crews after the maximum time of deployment is reached. This is how the MCC should increase the operational availability while restricting the deployment time for each individual sailor. By increasing predictability and limiting the duration of crew

deployments to a given maximum of number of days at sea per sailor and year, the German Navy intends to utilize the MCC to increase the attractiveness and predictability of service on board.

2. Experiences

Decommissioning the 206A class submarines in 2010 reduced the availability of platforms dramatically. Yet, the operational requirements were not simultaneously reduced to the same extent. A more intense use of resources with multiple crews led to the MCC “*Mehrbesatzungsmodell U212A (MBM U212A)*,” which was issued on April 1, 2011, by the German Navy. The concept resulted in the strict separation of crew and platform, with the objective to realize a 100-percent utilization rate of available submarines. Technical groups ensure the technical support during maintenance periods; a shore-based training and logistic environment supports the crews (Moritz, 2015).

For attractiveness of service, the maximum absence is limited to 120 days per year per individual. Operational availability of platforms and the limited temporal availability of the crew results in an arithmetic requirement of eight crews for the six available 212A class submarines (Moritz, 2015). Personnel shortfalls and vacancies, however, presently demonstrate that the navy has not been able to achieve the goal of maximum absence during the last decade. Even a reduced operational availability of the platforms caused by technical shortfalls has not led to the individual limit of absences being reached for all sailors.

The *Parliamentary Commissioner for the Armed Forces’ Report 2017* summarizes the experience so far with the MCC as follows:

[...] in the past year the Bundeswehr responded to the particular strains to which servicewomen and men are subjected in the Navy, above all due to the personnel gaps in this service branch, by reducing its presence on deployments and other commitments. Apart from this, the same specialized personnel are deployed again and again with various seaborne units. [...] The strain is supposed to be reduced by the multiple crew concept, under which crews take it in turns to man a vessel. However, it will only bear fruit if the various crews are sufficiently well staffed. High or low proportions of posts filled in assignment categories do not necessarily indicate whether there is a problem in the Navy. Even the loss of a single specialist can result in a vessel not being able to put to sea. This happened in 1 Submarine

Squadron, which has had to struggle with a difficult personnel situation in the past, particularly among its naval electronic technicians [...]. (Bartels, 2018)

In this excerpt, the Armed Forces Commissioner underlines the need for sufficient crew strength when implementing an MCC, as described in the example of the 1st Submarine Squadron. Based on the increasing automation and specialization on surface units like the F125, it is reasonable to apply the same conclusions to surface vessels.

B. MULTI-CREWING CONCEPTS IN THE U.S. NAVY

In *Alternative Sea Manning Concepts: Practices and Policy Implications* (Dolfini-Reed, Koopman, & Lawler, 2006), the authors investigate the different U.S. Navy sea manning initiatives and experiments from the early 2000s. All the introduced initiatives involve the optimal rotation of personnel while maximizing the forward presence of naval forces. The authors refer to the rotational crewing concepts:

- Blue / Gold (two crews one platform),
- Horizon (x number of crews per platform), and
- Sea Swap (one crew per platform, but the crews rotate on the platforms).

For all of these concepts the authors highlight the requirement that the U.S. Navy has contingency personnel sources readily available to fill upcoming gaps in manning. They suggest that extra manning pools hardly provide relief, neither on unforeseen gaps, nor on long-term gaps. Further, the introduced rotational crewing concepts are necessary when a navy used to operate as a result of these changes, the Bundeswehr comprises an aging force from which many experienced soldiers will be leaving in the coming years, and fewer similarly skilled young soldiers will be available to replace them large fleets now is developing new combat capabilities and platforms that are coherent with advancements in technology and reduction of crew size. A continued reliance on the bond between one ship and one crew raises the problem of increased coordination, e.g., in sea-training requirements. All rotational concepts, of course, share manpower concerns that affect sea and shore organization. At a given strength of the navy, additional billets for rotational

crews would negatively affect the number of available billets ashore. The increased organizational effort and the required support for rotational crewing, on the other hand, would require a higher number of shore billets. The authors assess that an increased force availability would correspond to an increased personnel base. Further, the authors discuss the challenges in providing sufficient training facilities for all crews to keep and maintain a high operational standard. A psychological side-effect of the decoupling of crew and platform is the lower identification of the crew with their ship; other effects include the loss of “corporate identity” or neglected maintenance. Besides the negative effects, the authors assess that the intact crew organization and the joint training may have a positive influence on the overall performance of a crew.

The findings of Dolfini-Reed et al. (2006) largely coincide with the long-term effects described by Labs and Gilmore (2007). The latter’s Congressional Budget Office paper discusses the different approaches and their potential drawbacks (less familiarity, reduced sense of ownership, complex administration, as well as effects on the crew’s proficiency, morale, and retention). The authors assess that these effects depend on the size of the crew or platform, the mission, and the rotational time. The goal of all introduced concepts is to increase the time a ship can be operational away from its home port, providing forward presence in different areas of operations.

Both studies essentially refer to the effects of multi-crew concepts on the overall forward presence of the fleet and readiness of units. Thereby, they assume the unlimited availability of staffing and occupation of services on the seagoing units. In both papers the authors do not investigate the influence of long- and short-term vacancies on the functionality of the presented concepts. Ronald O’Rourke (2010) supports those assumptions in Naval College Review. The detailed results and resources recorded during the experiments on the units by the U.S. Navy are not available to me in the preparation of this work.

The practicability of different concepts has been tested in the recent years; however, there is no data available considering the compensation of vacancies within the crewing system. Therefore, the model developed in this thesis contains the major factors and simulates the effect of vacancies on the composition of crews.

C. IMPACT OF VACANCIES ON CREW COMPOSITION AND EFFICIENCY

The field of team performance and team composition has been the topic of a number of research papers for the past 70 years. Most econometric analyses of organizational turnover suggest that there is a negative impact of member replacements in a team. I did not find studies that explicitly discuss the impact of vacancy-caused replacements on a crews' performance.

In their meta-analysis Park and Shaw (2013) reveal the degree of the relationship between turnover rates and organizational performance. The authors show that this relationship is significant and negative. The analysis is based on 300 turnover-rate-organizational performance correlations and 300,000 sample organizations and units over all fields of activities, including governmental organizations, education, medical, finance, and manufacturing. The authors recommend the distinction between turnover that is voluntary (the employee leaves the company at his or her own decision) and involuntary (the employment contract is unilaterally terminated by the firm). Involuntary turnover has a lesser effect on organizational performance ($\beta_1 = -0.01 SD$) than voluntary turnover ($\beta_1 = -0.15 SD$). The authors conclude that organizations must recognize that financial and workforce performance are at risk if turnover rates rise. The studies examined are primarily business enterprises whose performance can be measured by means of economic indicators; military organizations are not part of this meta-analysis. Therefore, I consider the validity of the results of the meta-analysis to be limited. In addition, the distinction between voluntary and involuntary turnover is generally inadequate in the case of seagoing units, as the turnover in this case is largely not due to the cessation of employment but to the replacement of vacancies.

In their article, Kacmar et al. (2006) discuss the role of turnover as an indicator that affects the unit-level performance. By observing managerial and crew turnover, efficiency, and performance at 262 Burger King restaurants, they create a structural equation model to analyze whether turnover has an effect on unit-level performance. Their secondary research questions determine that if there were effects, whether any mediating mechanisms exist, and what the value of a stable workforce is. Unlike Park and Shaw (2013), they only

watch for voluntary turnover. They explain the relationship between turnovers and efficiency according to a knowledge-based theory of organizations. The authors find that turnover does have an impact on unit-level performance, especially by a negative relation between crew turnover and efficiency. In particular, managerial turnover that is positively and immediately related to crew turnover has the highest effects on unit performance. Turnover may reduce the flow of tacit knowledge in the organization.

In “Team Member Change, Flux in Coordination, and Performance: Effects of Strategic Core Roles, Information Transfer, and Cognitive Ability” (Summers, Humphrey, & Ferris, 2012) the authors analyze conditions under which the change of team members may cause a decreased input-to-output conversion in team coordination. Reduced team coordination thus also entails a reduction in team performance. Summers, Humphrey, and Ferris introduce the concept of “flux,” which is an emergent state rather than a process; it describes the ability of the team to convert inputs to outcome via variation in coordination mechanisms. This output is not necessarily negative (Summers et al., 2012). In their study of 108 four-person marketing teams they found that the effect of change in team composition affects the flux and thus the team performance with a negative coefficient. Figure 1 shows that the more strategical the role, the more the reduction in information transfer affects the amount of flux that teams experience in their ability to coordinate their behavior effectively (Summers et al., 2012).

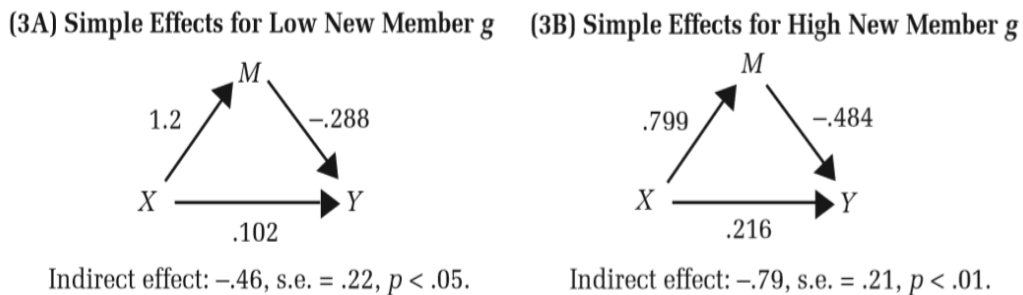


Figure 1. Effect of change in team composition of less (low g) and more influence (high g). Source: Summers et al. (2012).

“Dynamics between Member Replacement and Team Performance: The Role of Members’ Relative Attributes: Member Replacement and Performance” (Li & Gevers, 2018) analyzes the dynamics between member replacement and team performance. In their study the authors analyze the 367 replacements at the FIFA World Cup in 2014. They see replacements as difficult because of the potential gains and losses of a team’s resources in membership change. The primary advice on crew composition is to “*choose substitutes that are more competent than their predecessors*” (Li & Gevers, 2018). Li and Gevers analyze team replacements that are mostly driven by a weak team performance prior to the replacement. The replacement decision is—except for injury-caused replacements—made by the trainer who recognizes weaknesses in team composition and therefore purposefully modifies the team composition by choosing an individual that he or she assumes is presently more capable than the permanent. This study highlights the potential that lies in a moderate change in team composition. To achieve a positive effect, the exchange decision must not be made under the pressure of limited resources.

The introduced papers generally show a negative impact of turnover to team performance. I transfer those results to potential impacts for vacancy-related replacements within a multi-crewing organization. This turnover is assumed as neither voluntary nor involuntary. Park and Shaw (2013), Kacmar et al. (2006), and Summers et al. (2012) indicate that a turnover in higher positions (managerial turnover) may cause a greater disruption in accomplishment than crew turnover, by affecting the communication and information flow inside the organization. Li and Gevers (2018) show that a replacement may have positive effects if the substitute has superior characteristics compared to the permanent in its present characteristics. In case of available redundancies, a forced turnover may have positive effects on the crew performance.

D. OPTIMIZATION OF CREW AND PLATFORM SCHEDULES

In “Scheduling Patrol Boats and Crews for the Royal Australian Navy” (Horn, Jiang, & Kilby, 2007), the authors describe their approach to schedule activities for the ARMIDALE class patrol boats introduced in 2005 by the Royal Australian Navy (RAN). The authors developed a software tool—Crews, Boats, Missions (CBM)—for operational

use in solving and investigating multi-crewing in the RAN. Horn et al. (2007) outline the enormous combinatorial complexity of such a problem, finding the optimal number of crews and platforms for a continuous operational availability of the vessels. The CBM is a heuristic model divided into three modules:

- CBM FAS (Fleet Activity Schedule) assigns maintenance periods and missions to ships and crews with the objective to spread missions evenly.
- CBM COP (Combined Operations Plan) assigns scheduled activities to individual platforms and crews with the objective to maximize crew equality and reduce handover procedures.
- CBM LAT (Leave and Training Plan) allocates on and off periods to each crew. The objective is to maximize the crew satisfaction, which is difficult to quantify.

None of these steps considers any potential shortfall in platforms and crews. Although not explicitly stated, the CBM requires 100-percent availability of these factors. Restrictions that can occur due to unavailability are not considered.

Allen and Benoit (2003) conduct a study about potential gains in force availability of a multi-crewing practice. They create a model to evaluate the impacts of a 5:6 crewing model (five platforms to six crews) compared to an optimized 1:1 crewing model, where a single crew is assigned to a designated platform (classical crewing system). They compare the available and effective sea time. In a three-step analysis the authors determine an optimal schedule for the platforms and their assigned crews, minimizing the time lost due to crew changes. Considering the increased coordination requirements and personnel needs by utilizing more crews than platforms, the authors find that multi-crewing does not yield identifiable gains in availability for sea deployment.

In his thesis “Littoral Combat Ship Crew Scheduling” (Fitzsimmons, 2015), the author creates an optimization tool assigning crews to platforms during the construction process, minimizing disruptions. For the model he uses a mixed-integer, linear program. Fitzsimmons explicitly presumes that the crews are sufficiently manned at any given

period. Based on Brown, Dell, and Wood (1997), Fitzsimmons emphasizes the need for periodic adjustments and repetitions that compete with the necessary persistence to maintain an optimized solution.

III. MODEL DESCRIPTION

For the purpose of this model I define multi-crewing as the utilization of a number of crews to a lower number of platforms. Scheduling for crews and platforms occurs independently from one another.

The model describes the personnel flow within a number of crews C_i by computing the individual assignments to compensate for vacancies in the deployed crews. It is used to estimate the impact of permanent staffing shortages during the period of observation or non-permanent unexpected personnel drops during a sub-period t . I simulate the manning states for each run based upon overall manning rate, turnover coefficients, and sick quote. These manning states and a crew deployment schedule are the basis for the optimization model. The initial manning status at $t = 0$ is the basis for the first-stage optimization focusing on each individual over the whole period T . In the second step, I consider every subperiod t by itself individually, taking into account the overall optimization and the results from the previous sub-period $t - 1$. Finally, I summarize the assignments for each sub-period and use the sum as the basis for the filters and optimization in the next period.

A. CREW DESIGNATORS

Crews are indicated by the index i . A crew is defined as a self-contained system consisting of n individuals with k specializations. This self-contained system may also be used to describe crew elements or relevant crew excerpts, like single departments or other organizational elements

B. INDIVIDUAL DESIGNATORS

Each individual of each crew is encrypted with a five-digit identification number to allow identification and easy use in Microsoft Excel. To further distinguish it from other numbers and values, this identification number is marked with the letter X .

Example: X62009 (see Table 2).

X_{ijk} Individual identifier

Table 2. Example of individual designators.

X individual identifier	6 crew identifier (Crew 6)	2 availability identifier (# 2 for spec 001)	009 specialization identifier (009 = MechPO)	Antriebsmaat Number 2
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C. DEPLOYMENTS

A deployment in the context of this model is any time of seagoing absence for the whole crew as defined in Chapter IV, Section A. This can be absence caused by training, mission, exercises, or other reasons. Prioritization among those kinds of deployment may vary from time to time. A clear statement on prioritization is a leadership decision that cannot be derived concretely at this point. Therefore, I do not use the model to anticipate any prioritization among types of deployment; each of the deployments has the same priority. Figure 2 displays the different possible deployment states for each individual.

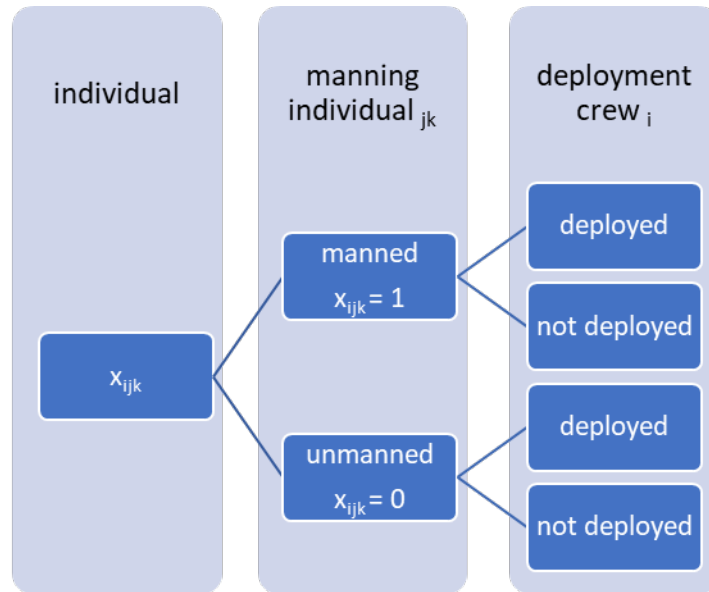


Figure 2. Individual's deployment states.

D. SCHEDULING

The period of observation (T) divides into a number of sub-periods t . The model's calculation relies on a schedule that reflects training, exercise, and deployment times. The planning authority sets this deployment schedule. The optimization of the schedule itself is not part of this thesis.

The schedule has 1.5 platforms at deployment throughout the period of observation. This implies that one ship is at the area of operation throughout the whole period of observation and another ship is at an area of operation for $T/2$. Crews conduct trainings and exercises at sea outside operational deployments on a platform available at home base. One platform is scheduled for maintenance throughout the period of observation. From this derives the requirement for three fully staffed operational crews, including a handover time in the area of operation that requires both the departing and the detached crews, and derives a need for a maximum of five fully manned crews at the same time.

E. PROBABILITY MODEL

In this section I introduce the probability set of individuals leaving and joining the crewing system. I differentiate between the three states: manned (M), unmanned (U), and temporarily absent (TA). The observed crewing system is a self-contained system; individuals can enter and leave over time. An individual entering the system changes the status of a billet from unmanned to manned. A billet is a job assignment for an individual within the crew, and it is assumed as manned if the variable x_{ijk} representing the individual equals 1. Once an individual has entered, the billet status can change to a limited temporary absence. If a temporarily absent sailor returns, he will always be prioritized for reembarkation to the crew. An individual leaving the system changes the state to unmanned, independent from its prior status. The following overview shows the probability model graphically. Figure 3 shows the different paths of status transition.

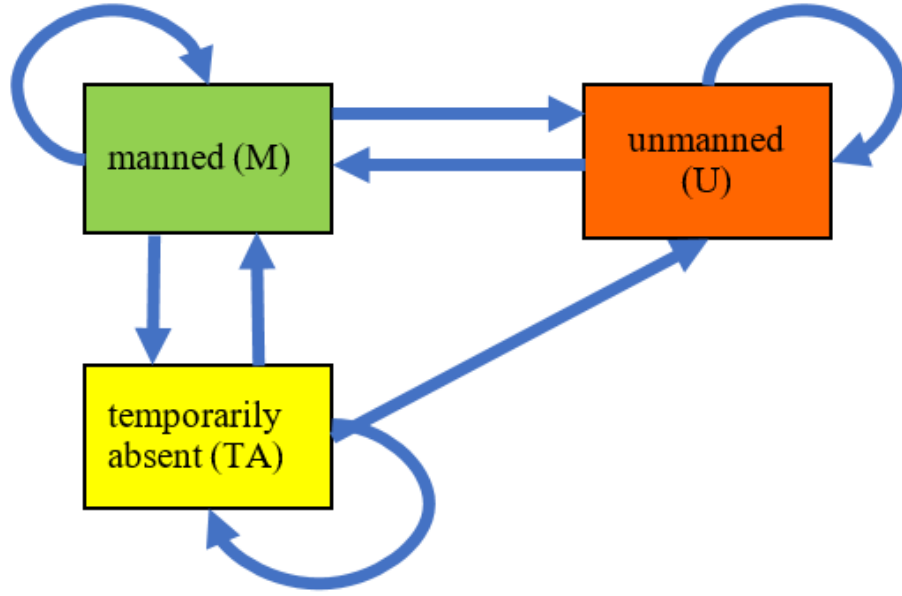


Figure 3. X_{ijk} Status overview.

Indices and index sets include the following:

M	Position is manned [$X_{ijk} = 1$].
U	Position is unmanned ($X_{ijk} = 0$); there is no individual assigned to the billet, vacancy.
TA	Individual is temporarily absent [$X_{ijk}(t) = 0$].
$P^{M,U,TA}$	The probability of each status is expressed as $P^{M,U,TA} \sim N(\mu, \sigma^2)$.
P^U	The probability a billet on board is unmanned at the initial period of observation $t = 0$.
$P^{(M U)}$	The probability an individual will leave the crewing system (e.g., retirement, chronic diseases, etc.).
$P^{(U M)}$	The probability an individual will enter the crewing system (e.g., new recruits).
$P^{(TA M)}$	The probability an individual will be temporarily absent (due to sickness, individual training, etc.).

$P^{(M TA)}$	The probability an individual will return from temporary absence.
$\hat{t}_{X_{ijk}}^{(M U)}$	The projected time to fill a vacancy with an individual X_{ijk} as a system inflow.

P describes the probability for the change of a billet from one status to another according to the availability of an individual who fits the billet's requirements. $P^{(M|U)}$ and $P^{(U|M)}$ describe the states of system in- and outflows. These are generally foreseeable at a time $t_{X_{ijk}}^{(M|U)}$ prior to the time of system entry $\hat{t}_{X_{ijk}}^{(M|U)}$ and will affect the optimization process once they are assigned.

F. OPTIMIZATION MODEL

The optimization model filters personnel supply and demand, and allocates workforce supply to workforce demand. This allocation takes place by optimizing the days of deployment for each individual in two steps:

1. Stage One Optimization and
2. Stage Two Optimization.

Both steps are described as follows.

1. Indices and Index Sets

i	Crew number indicator
I	Total number of crews' indicator
j	Specialization number indicator
J	Indicator of total number of specializations k in Crew C_i
k	Specialization indicator
D_i	Indicator of number of days of deployment for each crew i
D_i^S	Indicator of initially ($t = 0$) scheduled deployments for the whole period T
D_i^U	Indicator of unscheduled deployments for the whole period T

D_{limit} Indicator of the maximum days of deployment for each individual

The optimization model uses inputs from the crew simulation and the schedule of deployments. By dividing personnel into available supply and demand, the model filters the individuals by availability and specialization prior to each stage of optimization. Demand arises if a billet is not manned and the respective crew is scheduled for a deployment. Supply includes all available individuals who are not scheduled for deployment and do not exceed the maximum of days of deployment.

dem Personnel demand

$$X_{ijk}^{dem}(t) = \begin{cases} 1, & D_{X_{ijk}}^S \geq 1 \wedge X_{ijk} = 0 \\ 0, & otherwise \end{cases}$$

$supp$ Personnel supply

$$f(x) = \begin{cases} 1, & D_{X_{ijk}}^S \leq D_{limit} \wedge X_{ijk} = 1 \wedge D_{X_{ijk}}^S(t) = 0 \\ 0, & otherwise \end{cases}$$

While the decision variables for each step remain the same, the objective function and the constraints differ between the two steps. The objective function links the decision variables with the structural constants; these are the deployment days for each crew (D_i). The overall model, as depicted in Figure 4, requires two objective functions—one for each step—to consider dynamic changes during the period (T).

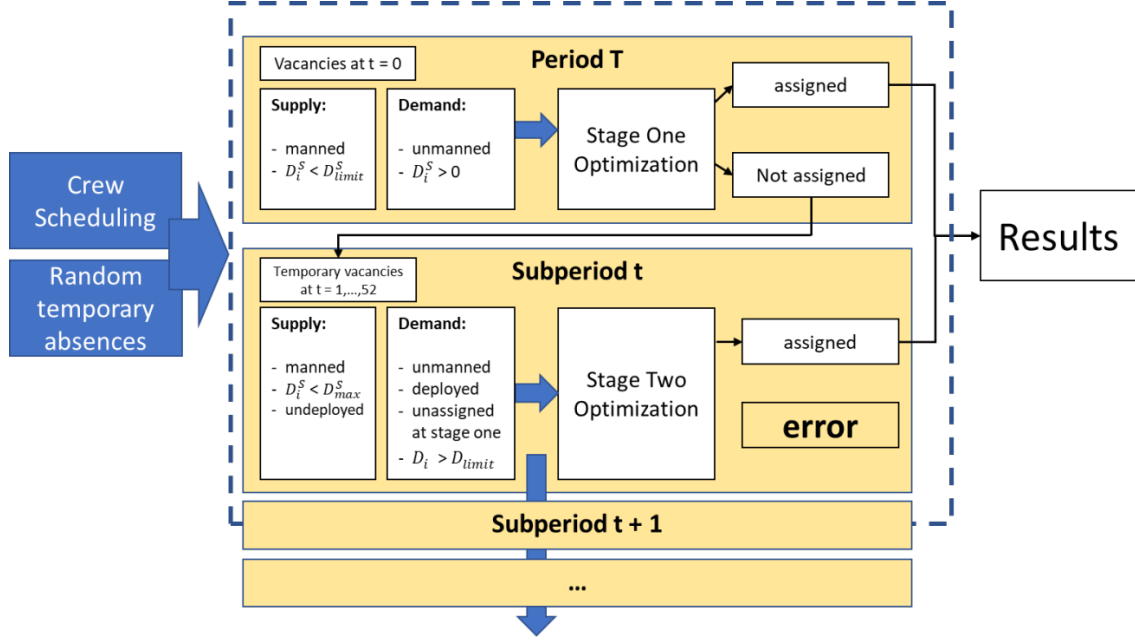


Figure 4. Assignment process.

2. Outcomes

The outcome of the objective function is the number of days of deployment for the individuals. Additional (“unscheduled”) days of deployment for an individual are designated with an uppercase U , days of deployment that were scheduled for individual x_{ijk} as a member of Crew C_i are scheduled with an uppercase S (“scheduled”).

$D_{X_{ijk}}$	Number of days of deployment for each individual X_{ijk}
$D_{X_{ijk}}^S$	Number of days of deployment scheduled for each individual X_{ijk}
$D_{X_{ijk}}^U$	Initially unscheduled Number of days of deployment for each individual X_{ijk}

3. Stage One Optimization

The linear optimization of the personnel allocations for period T (static) considers the initial personnel status at $t = 0$ and distributes available personnel with low load of deployments to vacancies in crews with long-term deployments. The purpose for this

approach is to obtain long-term solutions for deployed crews and minimize the impact of personnel changes during any deployment.

a. Decision Variables

A_{ij} Assignment of individual X_{ijk} to crew i (binary)

b. Formulation Objective 1—Optimization Period T

$D_{X_{ijk}}^U = A_{ij} * D_i$ is the number of additional days of deployment for each assigned individual. To minimize the additional days of deployment $D_{X_{ijk}}^U$ for each individual assigned, the objective function is:

$$\text{minimize } D_1^U = \sum_{i=1}^I \sum_{j=1}^{J_k} A_{ij} * D_i$$

c. Constraints

The Stage One Optimization includes five constraints. Exactly one individual X_{ijk} must man the position demanded in the crew (1). The manning process can only be allocated at most to one individual at a time to a position during a deployment (2). The decision of an assignment of an individual X_{ijk} to a deployed crew is binary (3); this implies that all decision variables are positive in their value (4). The sum of scheduled and unscheduled days of deployment for each individual X_{ijk} may not exceed the limit on individual absence (D_{limit}) (5). Thus, D_{limit} is given by the current policy of maximum days of deployment for each individual.

$$(1) \quad \sum_{i,j=1}^{I,J} A_{ij}^{dem} = 1$$

$$(2) \quad \sum_{i,j=1}^{I,J} A_{ij}^{supp} \leq 1$$

$$(3) \quad A_{ij} = \begin{cases} 1, & \text{if } X_{ijk}^{supp} \text{ is assigned to vacancy } X_{ijk}^{dem} \\ 0, & \text{otherwise} \end{cases}$$

$$(4) \quad A_{ij} \geq 0$$

$$(5) \quad D_X^S + D_X^U \leq D_{limit}$$

4. Stage Two Optimization

The linear optimization of the personnel allocations for sub-periods t (dynamic) considers the resulting vacancies for each period, by conducting a linear optimization for each period t , each individual, and specialization k . The outcomes in additional deployment days for each individual ($d_x^U(t)$) are summed and provide the basis for the next filtering and optimization process in period $t+1$.

a. Decision Variables

$A_{ij}(t)$ Assignment of individual X_{ijk} to crew i at subperiod t (binary)

b. Formulation Objective 2—Optimizations of Sub-periods t

The total deployment D_x is the sum of the scheduled and unscheduled deployments for each individual. The unscheduled deployment for a sub-period is the positive assignment decision for the respective sub-period. The sum of all assignments at all sub-periods for an individual results in the number of unscheduled days of deployment for the individual.

$$D_x = D_x^S + D_x^U$$

$$D_x^U(t) = A_x * d_i(t), \text{ where:}$$

$$D_x^U = \sum_{t=1}^T \sum_{i=1}^I \sum_{j=1}^{J_k} A_{ij}^S(t) * D_i(t)$$

The objective function results as follows:

$$\text{maximize } D_x(t) = D_x^S(t) + A_x(t) * D_i(t)$$

c. Constraints

The second stage of the optimization entails six constraints the objective function must meet. The maximum days of sea deployment D for each individual must not exceed D_{limit} days per year. This includes scheduled (D_S) and unscheduled (D_U) sea deployments. Scheduled sea deployments are scheduled deployments in agreement with the yearly deployment overview for each crew. Any embarkation of an individual to another crew is

defined as an unscheduled deployment for the individual (1). Exactly one individual X_{ijk} staffs the demanded position (2), while during the sub-period optimization process each individual is allocated only once (3). The allocation variable A_{ij} is binary (4). As long as an individual has not reached his or her specific maximum number of days of deployment and the originally assigned individual is not available, the individual embarked in the previous sub-period remains assigned to the crew (5). Further, all decision variables remain positive (6).

$$(1) \quad D = D_S + D_U \leq D_{limit}$$

$$(2) \quad \sum_{i,j=1}^{I,J} A_{ij}^{dem}(t) = 1$$

$$(3) \quad \sum_{i,j=1}^{I,J} A_{ij}^{supp}(t) \leq 1$$

$$(4) \quad A_{ij}(t) = \text{binary} \begin{cases} 1, & \text{if } X_{ijk}^S \text{ is assigned to vacancy } X_{ijk}^D \\ 0, & \text{otherwise} \end{cases}$$

$$(5) \quad D_{X_{ijk}}^U(t) \leq D_{limit} \wedge X_{ijk}^{dem}(t) = 0 \Rightarrow X_{ijk}(t) = X_{ijk}(t-1)$$

$$(6) \quad A_{ij} \geq 0$$

G. “RULE OF THUMB”

It is possible to estimate the sustainability of the MCC with a simple “rule of thumb.” Having i numbers of fully manned crews with the constraint of a maximum of D_{limit} days at sea per period T and Individual X_{ijk} , it is possible to ascertain

$$\text{Maximum Number of Ships at Sea} = \frac{i * D_{limit}}{T}$$

where:

i Number of crews available

D_{limit} Maximum deployment constraint (in days)

T Period of Observation (in days).

For example, having eight fully manned crews available and a constraint of 120 days of deployment per individual per period, the maximum number of ships deployments is $8 \times 120 / 365 = 2.63$. This suggests that during a one-year period two ships may be deployed a complete period of one year and one ship for about 63 percent of that time, or 230 days. Conversely, this rule can also be used to calculate the average required days available per billet or specialization to realize a required number of deployments per period. An average deployment of 2.5 ships per year would require an average availability of 114 days per Individual X_{ijk} . Nonetheless, this calculation does not reflect any dynamic issues. I will use this estimate to conduct a valuable guess whether the crew composition will sustain or fail the set requirements.

H. STEPPING THROUGH THE EXCEL/VBA MODEL

The Excel/VBA code contains the following steps:

1. Calendar Inputs

The Excel file contains a field to enter deployment dates for each crew. This allows individualizing the underlying schedule for the calculations.

2. Personnel Overview

The personnel overview contains information about the personnel status, providing information about name, assigned crew, billet identifier, individual/billet identifier. The staffing and deployment status shows the availability of each individual. The entries to this list are the basis for the crew model and can be edited manually.

3. Creation of Random Numbers

For the random number generation, I use the standard Excel number generator with a normal distribution.

4. Stage One Optimization

- a. Determine supply and demand for the whole period T according to the initial manning status. This presupposes that of absence per crew meets the limitation in the planning process.
- b. Solve for each specialization for the whole period T.
- c. Transfer solver solution to the crew schedule overview (overall change, overall additional days at sea for each individual).
- d. Transfer the additional deployment days for each individual to the crew overview.

5. Stage Two Optimization

- a. Determine supply and demand for each sub-period t according to random crewing.
- b. Conduct optimization process for each specialization.
 - i. Decision Variables
 - ii. Objective Function
 - iii. Constraints
- c. Transfer solver solution to the crew schedule overview (dynamic deployment, add up every week of deployment).
- d. Transfer the additional deployment days for each individual to the Crew Overview.

6. Collecting the Results

The whole year's assignments and the final days of deployment are transferred to the results sheet. Here I calculate the percentage of embarkations, the total number of embarkations, and the total number of unmanned billets for each period and each crew.

Uncompensated vacancies are marked and are stored with the circumstances under which a solution was not available.

IV. SIMULATION AND OPTIMIZATION

A. SETUP

The base setup for the simulations consists of eight crews. Considering current vacancies in the German Navy, particularly in technical areas, I use the crewing size of the F125 engineering department as the basis for my model crew. According to the manning plan this department consists of 52 persons, including officers and enlisted personnel with a background of mechanical, electric, electronic and information technology (IT) engineering. The division breaks up into 17 primary specializations indexed as k with j individuals in each specialization. The total strength of eight crews sums up to 416 individuals. The reduction in these numbers is due to the limits of available computer capacity to conduct the simulation and optimization. Since technical billets currently have, in many cases, the highest number of critical vacancies (Bartels, 2018), (Dewitz, 2016), the focus on this area is sufficient to obtain a reliable statement on the sustainability of the MCC. The optimization process does not consider secondary skillsets. (A list of related billets and specializations appears in the appendix.) Further, the model does not consider secondary personnel (TLC, OTC, staff and crew reserve) in the context of leadership and support, which is formally included in the MCC but has no direct impact on crewing. The decision not to consider the crew reserve is based on the existence of vacancies in the seagoing units. A reserve could only be formed if there were surplus personnel in the crews.

For the simulation of temporary absences caused by sickness, urgent trainings, or other individual reasons, I use the average sick-leave quota from Germany in 2017, as reported by the German Federal Statistical Office (Statistisches Bundesamt) (DESTATIS, 2018). DESTATIS defines the sick-leave quote as follows: “The sick leave informs about the extent of sick leave by employees. [...] The calculation only covers sick leave that exceeds an absence period of three days. The number of sick days should therefore be higher.” In 2017 the quota was 4.3 percent; for the simulation the sick-leave quota varies between 5 and 10 percent. The likelihood of another week’s absence following a one-week illness is about 35 percent (DESTATIS, 2018).

For the simulation of the crew strength, I use the Microsoft Excel random number generator with a normal distribution.

The duration a sailor remains on his assignment on a sea-going billet varies by rank and specialization. Based on an average assignment period of four years (BMVg, 2016), this results in a turnover of 25 percent per year. Due to overlaps in the assignment, there may be temporary vacancies if a successor is not available in time. In my simulation, turnover rates range between 0 and 25 percent to quantify these losses, where the maximum of 25 percent describes the greatest possible losses.

The underlying mission schedule for the simulations considers the following aspects:

- The average number of ships deployed is approximately two (1.5 in operational deployment, 0.5 in training and exercises).
- A ship's handover in deployment is assessed with one week (one sub-period t).
- A ship's handover in home port is negligible; the status of handover in home port is considered "not deployed," because the handover can occur during regular work hours.
- Prior to every operational deployment a consolidation phase on a ship must be conducted. The exception here is Crew 8.
- Duration of an operational deployment is approximately 90 to 100 days.
- Participation on national and international exercises is scheduled for 16 weeks per year. Participation requires an operational-ready crew, and participation can be used as the consolidation phase prior to an operational deployment.
- Ships' movements in port, as well as daily cruises for test and maintenance, are not considered as deployment.

- Port stays during deployments in foreign ports may or may not be considered as deployment depending on the type of deployment (operational deployments: yes, all others: no).
- The artificial schedule contains peaks on purpose in order to map the behavior of the influence of the vacancies under a high load of deployments (Week 18, Weeks 29 to 31).

The preceding assumptions and planning aspects rely on an approximately 50 percent sea-utilization rate of the units. For the general arrangement, the constraint for absences is set to 120 days per year (period T) and for each individual.

B. VARIATIONS

Based on the previously stated parameters, I performed the simulations and optimization processes shown in Table 3.

Table 3. Distribution of simulation runs.

#	Vacancy Rate	Turnover Loss	Temporary Absence
1	90–60%	10%	5%
2	90–60%	10%	10%
3	90–60%	0%	5%
4	90–60%	25%	5%
5	90–60%	10%	0%
9	90–60%	25%	10%
10	90–60%	0%	10%
11	82–60%	0%	5%
12	90–60%	10%	10%
6	100–50%	10%	5%
7	100–50%	10%	5%
8	100–50%	25%	5%
13	100–50%	0%	5%
14	100–50%	0%	10%
15	100–50%	0%	0%

#	Vacancy Rate	Turnover Loss	Temporary Absence
16 ³	100–50%	0%	0%
17 ⁴	100–50%	0%	0%

Each run includes the optimization for 52 sub-periods at each vacancy rate. With a setup of eight crews, this results in 568 calculated variations. Run 15, with no turnover loss or temporary absence, is the basis for the further analysis. The average calculation time for one run was 69 hours using an Intel Core i5-8500 Central Processing Unit (3.0 GHz with 8 GB of RAM).

Additionally, the simulations shared general settings similar to the standard setting, easing the constraint of individual absences from 120 days to 150 and 180 days per period T (runs 16 and 17). I refrained from reducing the number of crews, as this would require an adjustment of the overall deployment schedule, reducing the overall number of deployments. This adjustment would limit the comparability of the individual test series. Furthermore, a smaller number of crews does not necessarily imply a lower vacancy rate as vacancies cannot be attributed solely to a lack of applicants but also to training, sickness, or administration issues.

After running the specified setups, the next step is the analysis of the gained data.

³ Constraint of individual absence eased to 150 days per individual per period

⁴ Constraint of individual absence eased to 180 days per individual per period

V. ANALYSIS

The model for each setting produced results that were collected and written in a spreadsheet using a VBA algorithm to sort, prepare, and format the results for further analysis. This spreadsheet supplies a generated database of turnover and unmanned billets at different vacancy rates, turnover losses, and temporary absences. The analysis generally divides into the evaluation of turnover and unmanned billets, the overall failure criteria, and a specialization or individual approach to focus on analysis priorities.

A. EMBARKATION TURNOVER AND UNMANNED BILLETS

Figure 5 shows the partial result from the assignment process with a previously simulated 49 percent vacancy rate (Manning 51 percent), zero turnover losses, and no temporary absences.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	
1																
2	Crew 1	44%	44%	44%	44%	44%	44%	44%	44%	44%	44%	44%	44%	44%	0%	
3	Crew 2	0%	0%	0%	0%	50%	50%	50%	0%	0%	0%	0%	0%	0%	50%	
4	Crew 3	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	
5	Crew 4	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	
6	Crew 5	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	40%	
7	Crew 6	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	
8	Crew 7	0%	0%	0%	0%	52%	52%	52%	52%	52%	52%	52%	52%	52%	52%	
9	Crew 8	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	
10	Period	1	2	3	Horizontal (Value) Axis Major Gridlines						9	10	11	12	13	14
11		X41001	X41001	X41001	X71001	X81001	X81001	X81001	X81001	X81001	X	X	X	X		0
12		X21002	X21002	X21002	X32002	X32002	X32002	X43002	X51002	X51002	X51002	X65002	X65002	X65002		0
13		X26002	X26002	X26002	X42002	X42002	X42002	X45002	X53002	X53002	X53002	X82002	X83002	X83002		0
14		X13002	X13002	X13002	X13002	X13002	X13002	X13002	X13002	X13002	X13002	X13002	X13002	X13002		0
15		X14002	X14002	X14002	X14002	X14002	X14002	X14002	X14002	X14002	X14002	X14002	X14002	X14002		0
16		X15002	X15002	X15002	X15002	X15002	X15002	X15002	X15002	X15002	X15002	X15002	X15002	X15002		0
17		X16002	X16002	X16002	X16002	X16002	X16002	X16002	X16002	X16002	X16002	X16002	X16002	X16002		0
18		X11003	X11003	X11003	X11003	X11003	X11003	X11003	X11003	X11003	X11003	X11003	X11003	X11003		0
19		X21003	X21003	X21003	X31003	X31003	X31003	X82003	X82003	X82003	X	X	X	X		0
20		X21004	X21004	X21004	X32004	X32004	X32004	X42004	X51004	X51004	X51004	X51004	X51004	X63004		0
21		X23004	X23004	X23004	X33004	X33004	X33004	X43004	X63004	X63004	X63004	X63004	X63004	X64004		0
22		X13004	X13004	X13004	X13004	X13004	X13004	X13004	X13004	X13004	X13004	X13004	X13004	X13004		0
23		X24004	X24004	X24004	X34004	X34004	X34004	X51004	X64004	X64004	X64004	X64004	X64004	X83004		0
24		X31005	X31005	X31005	X41005	X41005	X41005	X61005	X61005	X61005	X61005	X61005	X	X		0
25		X21006	X21006	X21006	X28006	X36006	X36006	X44006	X28006	X28006	X52006	X61006	X61006	X61006		0
26		X24006	X24006	X24006	X36006	X43006	X43006	X45006	X52006	X52006	X55006	X65006	X65006	X65006		0
27		X13006	X13006	X13006	X13006	X13006	X13006	X13006	X13006	X13006	X13006	X13006	X13006	X13006		0
28		X14006	X14006	X14006	X14006	X14006	X14006	X14006	X14006	X14006	X14006	X14006	X14006	X14006		0
29		X15006	X15006	X15006	X15006	X15006	X15006	X15006	X15006	X15006	X15006	X15006	X15006	X15006		0
30		X16006	X16006	X16006	X16006	X16006	X16006	X16006	X16006	X16006	X16006	X16006	X16006	X16006		0

Figure 5. Screenshot from an Excel spreadsheet showing the assignments resulting from Vacancy Rate (VR) = 49%, TL and TA = 0%.

This section shows the manning for Crew 1 in periods 0 to 14. An individual identifier X_{ijk} (X00000) pinpoints the individual currently assigned to a certain billet. Any crew indicator i that does not match the observed crew represents an embarkation of an alternative manning. Any change of manning to the previous sub-period represents a turnover. In order to evaluate the embarkation turnover rate, I sum these turnovers:

$\vartheta_{ijk}(t)$ Embarkation turnover indicator for $X_{ijk}(t)$

$$\vartheta_{ijk}(t) = \begin{cases} 1, & X_{ijk}(t) \neq X_{ijk}(t-1) \\ 0, & otherwise \end{cases}$$

$\Theta(T)$ Total embarkation turnover

$$\Theta(T) = \sum_{t=1}^{52} \vartheta_{ijk}(t).$$

Zero indicates that the crew is not deployed for the respective sub-period t . Any billet marked X is unmanned for $A_{ij}(t) = 0$. Using the sum of all unmanned billets for each crew deployed, it is possible to determine a value as a basis for estimating the sustainability of the MCC.

$$X(T) = \sum_{t=1}^{52} A_{ij}(t), given X_{ijk}(t) = 0$$

I do not consider the transition from or to an unmanned billet as embarkation turnover. In order to depict the effects of vacancies, I plot $\Theta(T)$ and $X(T)$ as a function of the vacancy rate (VR).

$$Effect_{\theta} = \Theta(VR)$$

$$Effect_X = X(VR)$$

B. FAIL CRITERIA

Determining the fail criteria depends on a variety of factors, which basically reflect the decision maker's willingness and risk adversity to deviate from the standards. These decisions may be supported by defining minimum requirements for crewing under different circumstances. Finally, the decision is with the commanding officer who must ensure the

safety of the ship and crew in terms of operational readiness and safe participation in sea traffic. The subjective decision about minimum manning requirements may depend on factors like

- type of deployment (training, operation, exercise, etc.)
- level of crew training, or
- technical issues.

The automation of tasks and the reduction of crew size (Powers, 2016) lessen the potential deviations from optimum manning. Further, the minimum manning requirements also deviate from secondary and tertiary tasks of the respective individuals, like capabilities of firefighting, use of respiratory protection devices, engine room supervision, or Head of Department. At this point it is not possible to provide a reliable definition about these deviations from the standard requirement. I consider the MCC to have failed at a certain vacancy rate if the general manning requirements during deployment cannot be met. Assuming a required 100-percent manning rate, any vacancy during deployment will lead to the failure of the MCC.

C. SPECIALIZATION/CREW ANALYSIS

For diversification among crews, I compare the resulting turnover rate and resulting unmanned billets relative to crews' time of deployment.

$$X_{i_{rel}}(T) = \sum_{t_0}^{t_n} \frac{A_i(t)}{t_n * t_{deployed}} \mid X_{ijk}(t) = 0$$

$$\theta_{i_{rel}}(T) = \sum_{t_0}^{t_n} \frac{\vartheta_{ijk}(t)}{t_n * t_{deployed} * X_{i_{rel}}(t)}$$

This method should reveal the differences in deployment time for each crew. For differentiation among the required manpower of each specialization, I choose an equal approach, indexing the specialization indicator k for each specialization relative to the number of individuals per specialization.

$$X_{k_{rel}}(T) = \sum_{t_0}^{t_n} \frac{A_k(t)}{t_{deployed} * \frac{\sum_{i,j}^{I,J} X_{ijk}}{I}}$$

$$\theta_{k_{rel}}(T) = \sum_{t_0}^{t_n} \frac{A_k(t)}{t_{deployed} * \frac{\sum_{i,j}^{I,J} X_{ijk}}{I} * X_{k_{rel}}(t)}$$

D. STATISTICAL ANALYSIS

I analyze the generated database with a regression analysis (Ordinary Least Square, or OLS) using STATA. The underlying database consists of the results of the turnover and the unmanned billets depending on the parameters VR, TL, and TA. The analysis uses the following defined variables:

- Unman = unmanned billets ($X_{ijk}(t) = 0 \rightarrow X(T)$)
- Assign = turnover/ assignments due to embarkations ($\vartheta_{ijk}(t) \rightarrow \theta(T)$)
- VR = 1 – Vacancy Rate = (Manning Rate)
- VR2 = VR²
- Turn = Turnover Losses (from the setting)
- Temp = Temporary Absences (from the setting)

The VR² is introduced to reflect the exponential shape of the function. Unman and Assign are functions of the variables VR, VR2, Turn, and Temp.

$$Unman = \beta_0 + \beta_1 * VR + \beta_2 * VR^2 + \beta_3 * Turn + \beta_4 * Temp$$

$$Assign = \alpha_0 + \alpha_1 * VR + \alpha_2 * VR^2 + \alpha_3 * Turn + \alpha_4 * Temp$$

VI. RESULTS

A. UNMANNED BILLETS AND TURNOVER RATE

According to the Rule of Thumb as described in Chapter III, the schedule requires an average manning status of 70.9 percent in order to keep a 120-day limit of absence for each individual. This implies that all vacancies are spread evenly over all specializations and crews. Further, temporary absences and losses due to turnover are not included in this short calculation.

First, I compare the vacancy rate with the overall number of unmanned billets during deployments. The evaluation shows an increase in the number of billets, as shown in Figure 6, that cannot be manned due to general vacancies. This relationship exists in all observed variations of turnover losses and temporary absence.

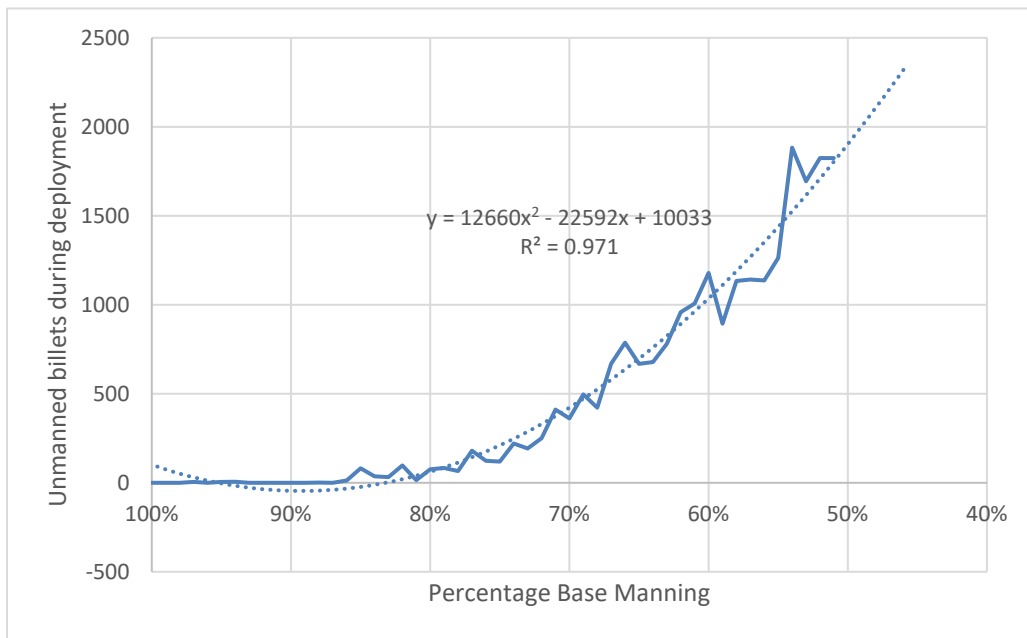


Figure 6. Unmanned billets VR = 50–100%, TA and TL = 0%.

With increasing vacancy rates, the total turnover rate diminishes due to fewer personnel available for replacements in other crews. This effect is consistent with my

expectations about the overall turnover rate and further confirms the validity of the model. A higher temporary absence rate increases the total number of unmanned billets and the turnover rate. A higher general turnover rate reduces the number of vacancies, but this coefficient is not statistically significant.

Using the simulation database, I conducted a regression analysis (OLS). Due to the obvious exponential dependency, it was necessary to create the variable VR2 (VR * VR) to represent the exponential form of the function. The evaluation in STATA yielded the following result depicted in Figure 7:

	(1) Unmanned Billets	(2) Embarkations
Vacancy Rate	-16849.465*** (1077.300)	6896.709*** (1401.780)
Squared VR	9226.533*** (672.084)	-5296.482*** (901.548)
Temporary Absences	-6.478*** (0.946)	19.504*** (1.612)
Natural Turnover L _{ns}	-1.400 (1.270)	2.766 (1.861)
Constant	7732.703*** (424.829)	-1368.569* (535.521)
Observations	510	510
R-squared	0.804	0.369
Standard errors in parentheses		
* p<0.05, ** p<0.01, *** p<0.001		

Figure 7. Stata result of the regression of the dependent variables Unmanned Billets and Embarkations on VR, VR2, TA, and TL.

The coefficients for VR, VR2, and Temp are statistically significant on a 1 percent level. The variable Turn seems to have impact, but in its present distribution among only three possible values, I cannot prove its significance.

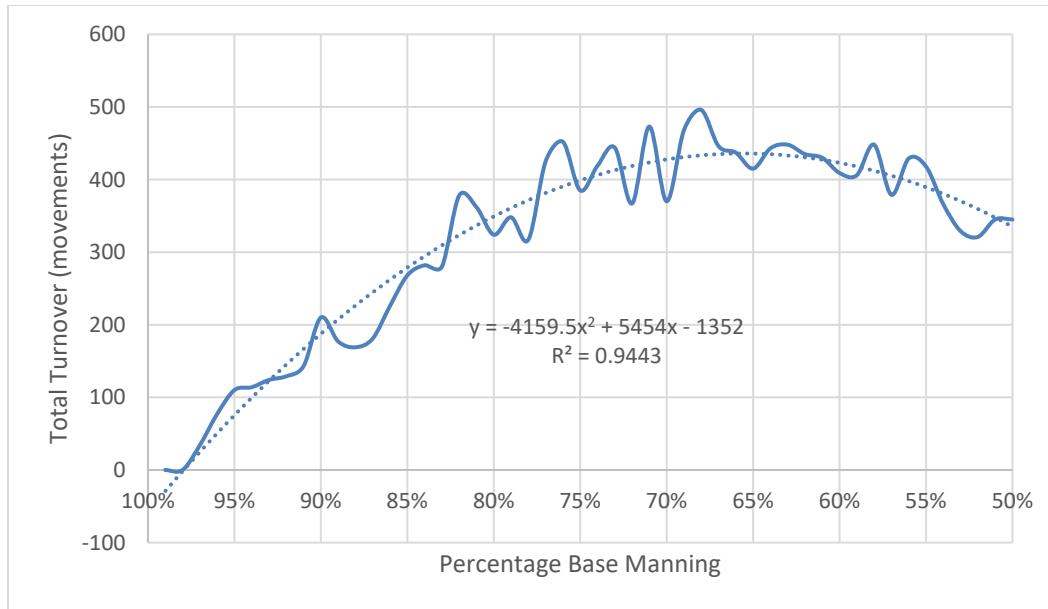


Figure 8. Total turnover at VR = 50–100%, TA and TL = 0%.

In the area of turnovers caused by embarkations, there is a similar picture (Figure 8): Turn is not statistically significant; VR, VR2, and Temp are. The evaluation of the simulation data from Run 15 (without turnover losses and without temporary absences) is based on the following function:

$$y = 12660x^2 - 22592x + 10033$$

The function results in a manning rate of 83.2 percent (VR = 16.8%), which is necessary to achieve a complete occupancy of the billets. For the averaged values from the regression analysis (50–100%), this results in a value of 81-percent minimum occupancy to ensure sufficient crewing for the present schedule. The first shortfalls occur very early, especially in specializations that have a high vacancy rate or in specializations that are few in number, where even a low number of vacancies has a great impact.

Figures 9 and 10 show a scatterplot of the total number of turnovers and the total number of unmanned billets related to VR. The exploration of all runs and their fitted values confirms the prior findings. The number of unmanned billets is an exponential function of the VR. The total turnover peaks at a VR of about 70 percent.

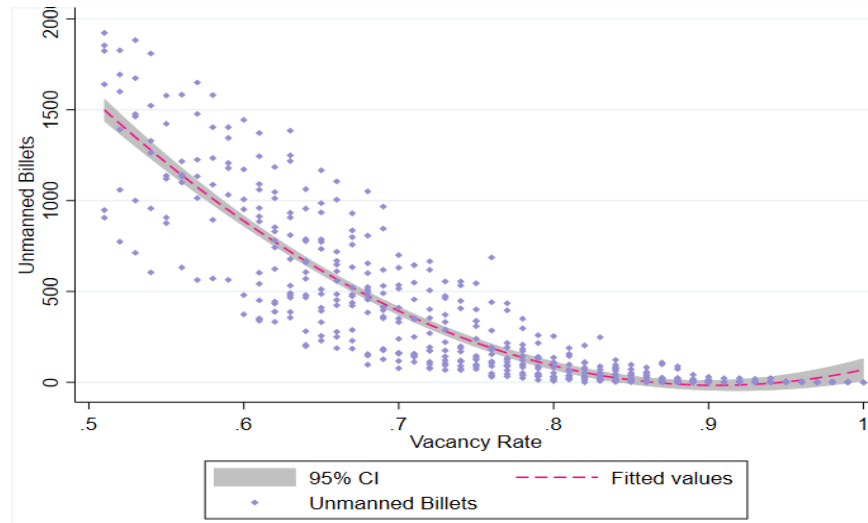


Figure 9. Data analysis (Stata) of runs 1 to 15 including fitted values (Unmanned Billets).



Figure 10. Data analysis (Stata) of runs 1 to 15 including fitted values (Unmanned Billets).

B. ANALYSIS OF CREW AND SPECIALIZATIONS

Following is a comparison of the occurrence of absolute and relative values in terms of assignment turnover and unmanned positions. The relativity refers to the scheduled deployment time of each crew and the manpower strength of each specialization. Figure 11 shows the total number of unmanned positions per crew. Since the deployment time

does not differ fundamentally (except for Crew 6, which is not deployed at all), the difference between the relative and absolute values is negligible. The same behavior can be observed in the turnover diagram.

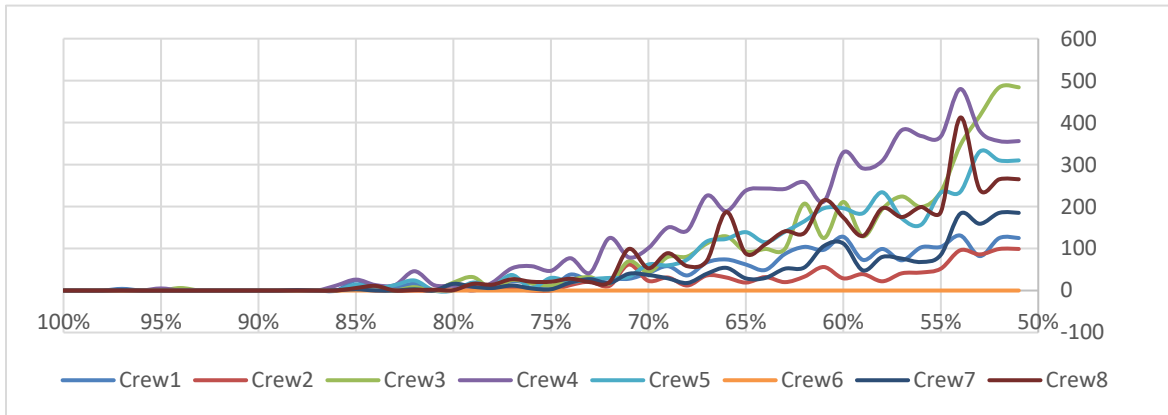


Figure 11. Unmanned positions crew-wise (total).

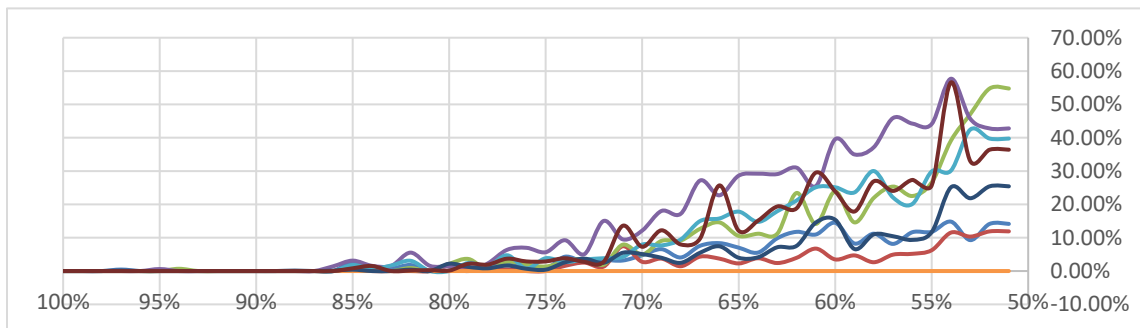


Figure 12. Unmanned positions crew-wise (relative).

In the specializations the relative difference is clearer. In order to highlight the differences between the individual specializations, I have compared underlying data of Figures 11 and 12 with the billets of highest and lowest numbers of employees. Specializations 001 and 005 (SchiffsTStOffz and SchiffsTechnOffz) are both available once in each crew. When fully occupied, eight individuals are available for the whole crewing cycle. Billets 002 and 006 (SchiffsBtrbTMAat and EliTMAat) have a force of six and eight individuals, respectively. Figures 13 and 14 display the relative impact of

vacancies on turnovers and unmanned billets. As expected, the proportion of relative failures for both specializations is almost the same.

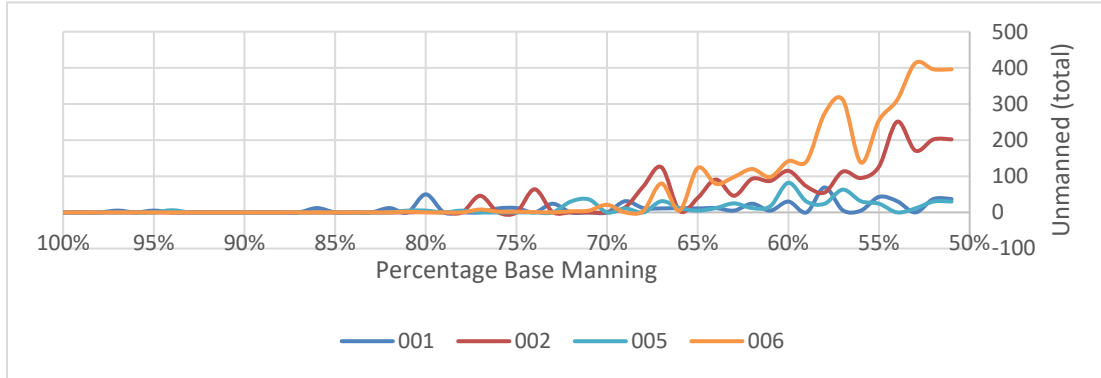


Figure 13. Unmanned billets specialization-wise (total).

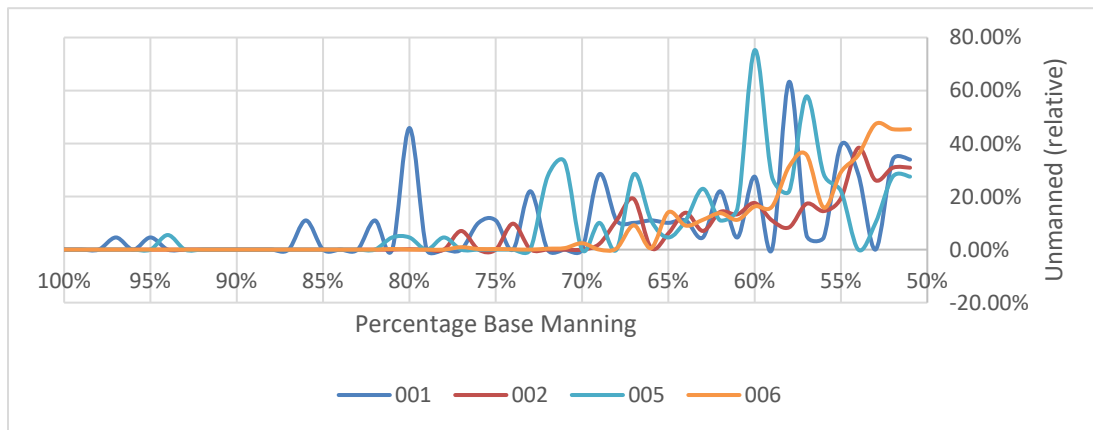


Figure 14. Unmanned billets specialization-wise (relative).

C. SCHEDULING

As expected, the critical points in scheduling turn out to be critical in manning, as displayed in Figure 15. Turnover and unmanned billets are peaking in periods 18, 30, and 45 to 46. Periods 18 and 30 are the ones with the most scheduled deployments. Periods 45 to 46 have three deployments each, which does not fundamentally exceed the average deployment rate. The shortfalls in the later period arise from the consumption of replacement resources.

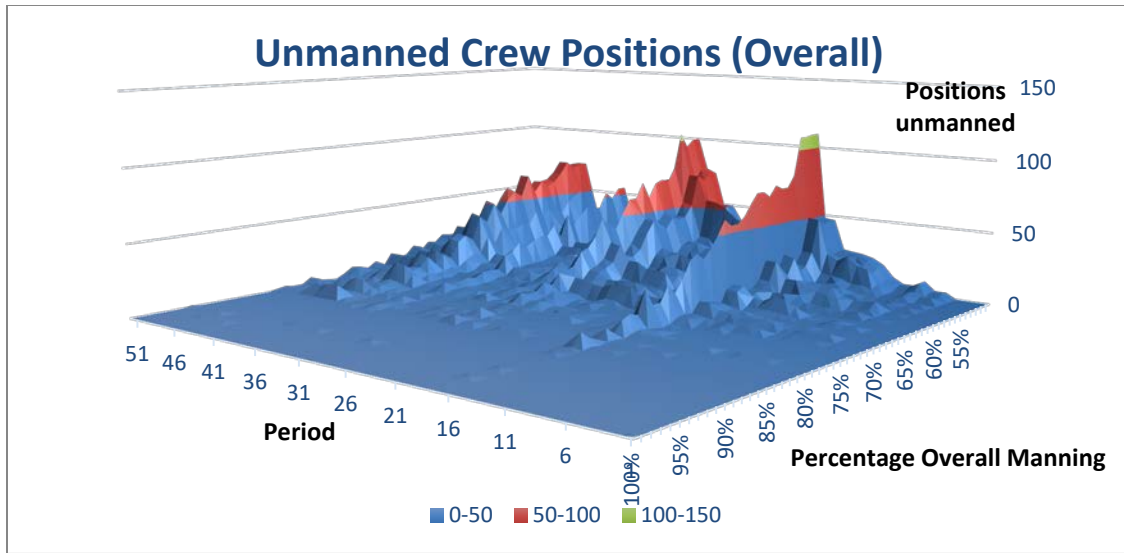


Figure 15. Unmanned crew positions VR = 50–100%, TL and TA = 0% for each sub-period t .

The embarkation turnover rate (Figure 16) remains high throughout the whole period T , peaking at the beginning of the cycle of the high deployment rate for the ships and crews.

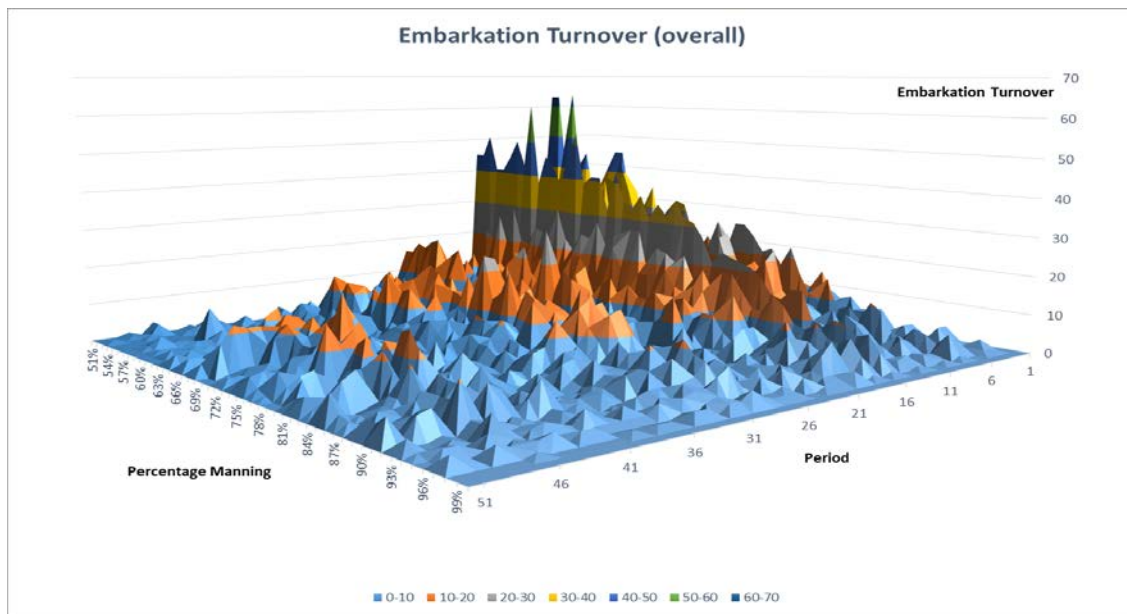


Figure 16. Embarkation turnover, VR = 50–100%, TL and TA = 0% for each sub-period t .

D. IMPACT OF TURNOVER ON CREW PERFORMANCE

Ship handling and operational deployment is a high-level team effort that requires individual performance brought together with a high-level of team performance. The coordination among the warfare areas (ASW, ASuW, AAW, and Asym), Task Force, internal and external battle, administration, seamanship, and other fields requires a high level of team coordination and knowledge.

According to Park and Shaw (2013), turnover has a negative impact on team performance, especially if the turnover is voluntary from the employee side. Involuntary turnover forced by the employer (e.g., by early termination of the employment relationship – “firing”) also has a negative effect, but it is significantly weaker, as companies primarily separate from low-performing workers. In the German Navy, the turnover situation is different. Volunteer turnover is seldom initiated by the sailors but is caused by the expiration of contracts having no option of extensions. Furthermore, an outflow of high-performing personnel also arises through active promotion to higher-quality training or to higher-grade ranks and billets. In addition to the turnover resulting from the inflow and outflow of personnel in the form of regular personnel movements, the compensation of vacancies from other crews results in additional turnover. This additional turnover correlates with the number of vacancies. In the simulation and assignment process I found that with a higher vacancy rate, the turnover increases. Consistent with the meta-analysis of Park and Shaw (2013) the higher vacancy rate would result in a lower team performance. This finding is consistent with Kacmar et al. (2006), who present turnover as a key predictor in determining the unit-level performance by reducing the knowledge flow within the team. This applies in particular to tacit knowledge, which De George (2012) in his thesis describes as “personal knowledge commonly acquired through situational experience, deeply rooted in action and in specific context” (Ambrosini and Bowman, 2001). He further states that “tacit knowledge has come to be referred to as broad know-how knowledge that is hidden or implicit within an organization” (Kacmar et al. 2006).

Summers and Humphrey (2012) illustrate this loss of tacit knowledge in a flux of team coordination, which has more impact the higher the affected rank is. In my simulation I found that specializations with fewer crew members assigned are more affected by

turnover and unmanning due to vacancies than specializations that can rely on a broader personnel base. This applies regularly to management positions that have a smaller staffing level and are not always redundant. Li and Grevers (2018) point out that a certain amount of turnover can have a positive effect on the ability of a team to transfer new work processes and ideas from one team to another. In the German Navy, with its relatively rigid processes and procedures, this positive effect occurs but to a much lesser extent. Furthermore, often the curtailment of embarkation complicates the complete integration of the supporting forces into the crew.

E. RESULTS RELATED TO OTHER OPTIMIZATION APPROACHES

All in Chapter III described MCC and optimization tools base on a “sufficient” or 100-percent crew strength. With my model, I was able to show that vacancies in a crew system can certainly lead to restrictions in the sustainability of multi-crew models. The manning problems can be traced over years. The requirement of completely filling individual specializations shows that intention and reality sometimes differ. It is therefore important to include these potential personnel shortfalls in the planning process and to find medium- and short-term solutions. As a long-term solution, I see a 100-percent staffing of the units. Chapter VII includes more detailed recommendations for achieving this goal.

Besides the vacancies, Allen and Benoit (2003) state that the gains in ships’ availability from using an MCC are minimal. Horn, Jiang, and Kilby (2007) explain that the factor of crew satisfaction as the last objective of their schedule optimization process is difficult to capture and to quantify. The approach of limiting the deployment time of each individual is one possibility to consider. Individual preferences differ and therefore the constraint deployment time is not necessarily an indicator for increasing attractiveness of seagoing billets.

Dolfini-Reed et al. (2006) find that multi-crewing is a possible option to increase the forward presence in times of fewer available platforms, reduced manning, and advanced technology. The authors describe that the separation of crew and platform can undermine the crew members’ sense of identification with their ship. This diminished sense of identification can lead to generally poorer handling of the entrusted material, so that

problems in the field of repair and maintenance can occur. In contrast, the authors expect a greater sense of identification among the crew, as the crew stays together as a unit. My results show that the unity of the crew cannot be maintained with an increasing vacancy rate. The higher the vacancy rate, the more it affects the turnover and the final manning of each crew. Changing crew compositions may lead to a loss of inner cohesion of the crew, while its individuals get embarked to other crews regularly.

F. EASING THE CONSTRAINT OF INDIVIDUAL ABSENCE

Facilitating the restrictions on 150/180 days of maximum absence for each individual provides the expected effects. The critical vacancy rate at which the required positions can no longer be filled increases. Figures 17 and 18 illustrate the unmanned billets and the overall turnover resulting from an absence constraint of 150 days per individual.

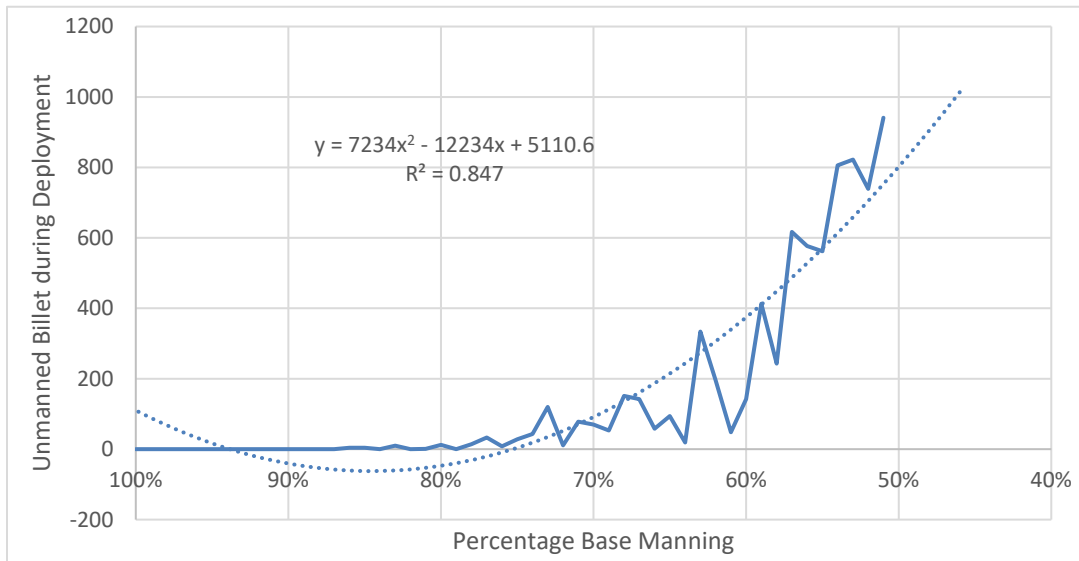


Figure 17. Unmanned billets VR = 50–100%, TA and TL = 0%, constraint eased to 150 days per period.

Assuming a polynomial equation for the unmanned billets during deployment, the vacancy rate at which all deployments can be manned is 24.7 percent.

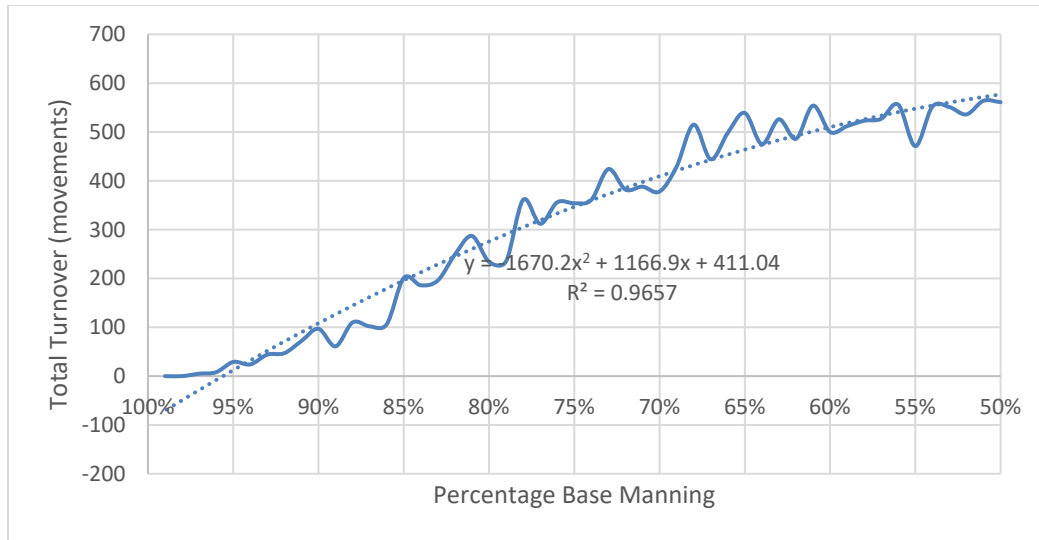


Figure 18. Total turnover at VR = 50–100%, TA and TL = 0%, constraint eased to 150 days per period.

At the vacancy rate of 75 percent the total turnover rate according to the simulation is 347 turnovers in one period. This is a significant drop from the turnover rate at the constraint of 120 days of deployment per individual. Figures 19 and 20 show this impressively.

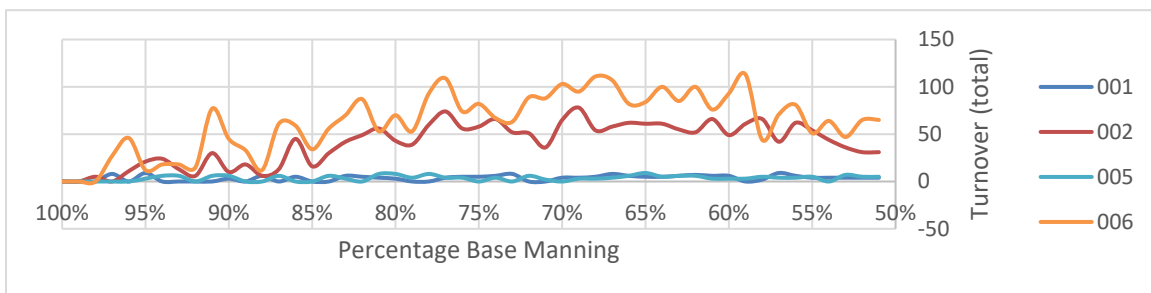


Figure 19. Absolute turnover for selected billets at a constraint of 150 days of deployment per individual.

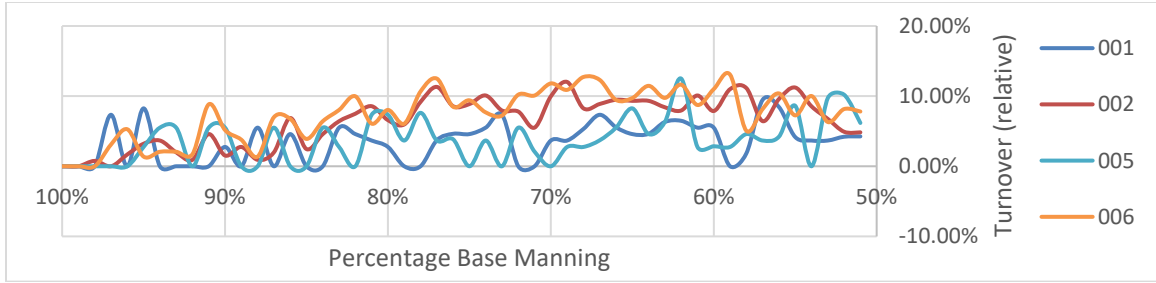


Figure 20. Relative turnover for selected billets at a constraint of 150 days of deployment per individual.

The effect of relative and total turnover for specializations with a high number of personnel and a low number of personnel appears more pronounced compared to the constraint of 120 days of absence per individual. Figure 21 shows the clearly relaxed personnel situation with an absence constraint increased from 120 to 180 days. The critical areas in the calendar remain, albeit with lower default manning rates. Turnover is lower; therefore, the higher constraint has an overall positive effect on the performance and the availability of the crew. On the other hand, this can lead to a reduction in the attractiveness of the service on seagoing units due to the longer absence of individuals, especially in short specializations.

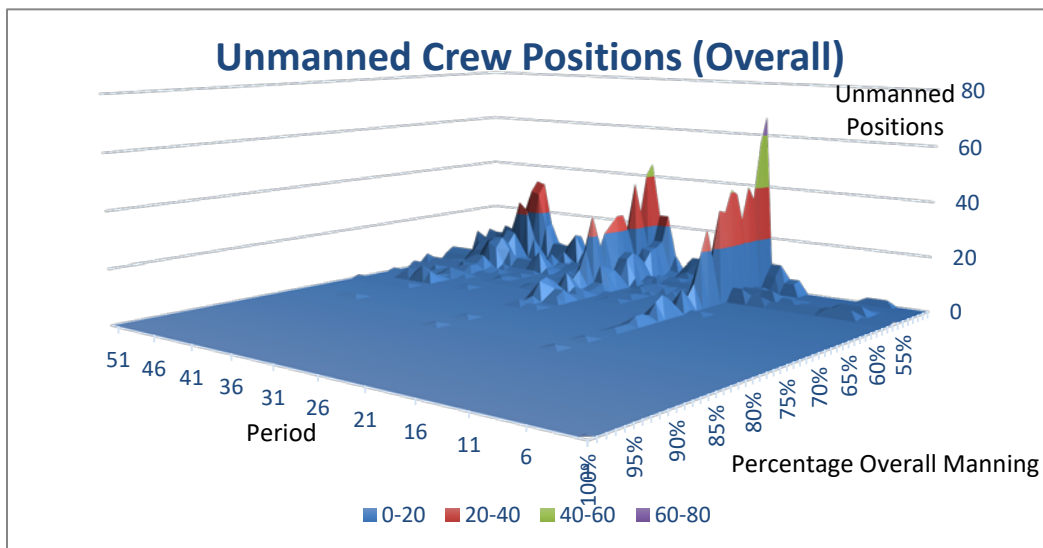


Figure 21. Unmanned crew positions VR = 50–100%, TL and TA = 0% for each sub-period t for a constraint of 180 of maximum individual absence.

VII. CONCLUSIONS AND RECOMMENDATIONS

As noted in Chapter II, previous studies on optimizing schedules for crews and available platforms do not sufficiently consider personnel shortfalls that may have an imminent effect on the MCCs, although some authors consider the need for adequate manning. In my model, I simulate these possible personnel restrictions. In doing so, I have deliberately chosen to construct a very abstract model in order to obtain the essential results in the field of unmanned billets and overall turnover.

A. LIMITS

Due to its relative simplicity, the model has some limitations. First, it does not reflect the on-the-job experience and additional specializations of individual crew members. Taking these into account could ease the challenges on one hand, by providing a higher interchangeability among the individuals; a more experienced sailor or any sailor with an additional skillset could compensate for single shortfalls. On the other hand, required secondary and tertiary specializations could increase the complexity, because now a set of skills and specializations needs to be replaced. Second, the model does not distinguish between different types of deployments; each deployment has the same value and requires the same base manning. I did not differentiate between different deployments, because any of these priorities is a command decision of the scheduling authority. That is the same for the personnel crew setting for different deployments. The final authority of assessing the sufficiency of personnel strength for the deployment lies in the hands of command.

B. FINDINGS

According to the results and the literature discussed in Chapter II, a higher number of vacancies causes a higher turnover rate up to a certain point, where billets cannot be manned anymore. The literature suggests that turnover and concomitant changes in the composition of the crews have a measurable impact on the crew's overall performance.

The vacancy rate has a significant impact on the sustainability and crew performance in an MCC. The simulation process shows that is the vacancy rate has an effect on the sustainability and performance of an MCC. Organizations implementing an MCC therefore must consider the average manning status of their crews in the personnel and organizational planning process already. I estimate that the manning rates as shown in Table 4 are required to conduct deployments under the given constraints of manning and individual absence adhering to a 100-percent manning policy during deployment.

Compared to the results gained by the application of the rule of thumb, the optimization model results in significantly increased staffing requirements as shown in Table 4. While in the rule of thumb there is only a linear allocation of existing resources to demand, the introduced optimization model takes into account any short-term, temporary absences of personnel.

Table 4. Required manning rate under different constraints of individual absence.

Maximum Individual Absence	Required Manning Rate based on the Model	Required Manning Rate based on the Rule of Thumb
120 days	83.2%	70.9%
150 days	75.3%	56.5%
180 days	73.7%	46.2%

The simulation shows that the number of unmanned positions increases exponentially with the vacancy rate. The overall turnover shows a negative parabolic shape; it increases with the vacancy rate up to a certain point until it decreases again. At this point, the number of vacant positions is so high that a replacement for other crews is no longer possible and billets remain vacant instead of being replaced by others. Further, this study has shown that an increased turnover rate may lead to reduced crew performance.

The impact of vacancies on different specializations depends on the number of personnel of the observed specialization. This follows the *law of the small number*, after

which the impacts of conditions on small groups have a relatively larger consequence than for large groups. Large groups have more redundancies to replace vacancies than have small groups.

When scheduling, the simulation confirms that in sub-periods, where more than an average number of units are at sea, it is difficult to allocate the crews. In a non-prioritized environment this circumstance increases with every expired sub-period. The individuals' available time is consumed due to the embarkations to other crews. At the end of the scheduling period time resources are no longer available.

Moreover, increased turnover and vacancies may reduce the cohesion within crews, which is already potentially endangered by the separation of ship and crew. Especially in this point, I contradict my sources, which predict with this separation an impeded cohesion among single crews.

C. RECOMMENDATIONS FOR MANNING AND VACANCY MANAGEMENT

Considering the limited availability of personnel in various specializations within the German Navy over the past years (BMVg, 2016) and the results of my simulation, it seems appropriate to include the existence of these vacancies into the planning process. According to the available results of this thesis, various options arise, which can be implemented individually as well as together in part. These options represent simplified structures and procedures that can be understood as an incentive and an idea to apply the results of this thesis.

(1) Increase the Organizational Structure and Create Higher Redundancies

The creation of redundancies depends on their origin. If they result from general shortfalls in recruiting, an increase of the organizational structure would not generate a higher availability of personnel but only a higher rate of vacancies. Further, this would increase the organizational structure. The enlargement of the organization structure would be a long-term solution and would miss the actual, acute problem. At a given strength of the navy, the increase of seagoing billets would be at the expense of shore billets (Dolfini-

Reed et al., 2006). Recruitment must consider the failure rate that may occur during training, and recruit accordingly.

(2) Adjust the Constraint of Individual Absence

The results with the eased constraint of individual absence show that an increased limit on the length of absence for each sailor also increases the general availability of personnel and therefore the operability of the fleet. This opens up various alternative courses of action, which can lead to a general or partial increase in availability. The permanent increase for all would be at the expense of the desired increase in attractiveness of service by reducing the permitted duration of absence. Potential consequences would be a negative impact on the recruitment of young talent, which will further affect the availability of staff and possibly create more vacancies.

Furthermore, the results of the present results also suggest the temporary adaptation of constraints for individual specializations and billets. According to Fitzsimmons (2015) and Brown, Dell, and Wood (1997), an initial and regular review of parameters could deliver a reliable estimate of the personnel needs for the next period. If implemented once a year, the adjusted constraint for one period would at least increase predictability of service for the upcoming cycle, giving an estimate of potential absence for each specialization. The tool I have developed for this analysis could be used to calculate the potential outcome, given certain parameters.

(3) Adjust the Crew Scheduling

The results indicate that acute vacancies occur in an environment of extraordinary burdens; this corresponds to the expectations. The planning of the crews depends on the operational tempo, as well as on the need to provide sufficient maritime power in due course. A schedule designed to fulfill personnel needs is not appropriate in every situation. In order to resolve the greatest conflicts between operational and personnel necessities, a detailed assessment of the personnel situation at different points in time can be carried out with the help of the present simulator. With knowledge of these shortfalls, planners may adjust the schedule, if this is operationally feasible.

(4) Consider the Shore Deployment

All resources displayed in this thesis assume the availability of crews for the optimization of schedules. My optimization model provides a solution for sufficient crewing during the deployments. This creates additional turnover that has effects on crew performance as discussed in Chapter VI. The model does not consider the time off seagoing deployments that is necessary for crew training and cohesion. In order to provide sufficient time for preparation, I suggest introducing a schedule item for crew cohesion or pre-deployment training. This item needs to be treated like any seagoing deployment item and highly prioritized. This would avoid exchanging personnel to other crews during this training period in order to keep crew performance at a high level.

D. RECOMMENDATIONS FOR FURTHER RESEARCH AND ANALYSIS

The most fundamental element for further investigation and research in this area is the implementation of the simulated data into, and the collection of data from, real life. Therefore, it is necessary to collect crew assignments and personnel movements throughout several periods to compare real data with the simulated data. Further research should use this updated data to improve the details of the simulator and to generate predictions that are more accurate. Further, the impact of vacancy-caused turnover on crew performance in a military environment requires further evaluation.

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