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Automatic Production Planning for the Construction of Complex Ships

Proefschrift

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Contents

Summary

European shipyards specialize in building complex ship types including offshore vessels, yachts, dredgers, and cruise ships. One key difference between these ships and the simple cargo ships typically built in the Far East is the amount and variety of mission-related equipment required to operate the ships. Technical spaces of complex ships are numerous and densely packed. Outfitting is the shipbuilding process of installing this equipment and its supporting components (e.g. piping, ducting, and cabling). Most shipyards do not adequately plan the outfitting process. Instead, high level schedules are typically provided to outfitting subcontractors. These schedules indicate the time windows during which they must complete their installation tasks. Conflicts between the different stakeholders are addressed during weekly meetings. This outfitting planning approach is characterized by disorganization, poor communication, and a lack of transparency. As a result, the outfitting process of European shipyards is often plagued by delays, rework, and sub-optimization.

A ship is constructed by first building large steel blocks, referred to as sections. Steel parts and profiles are welded together to create sections during the section building process. At the conclusion of section building, time is reserved for installing components in a section. The hull of the ship is formed by welding these sections together on a slipway or drydock. This process is referred to as erection. European shipyards mainly focus on planning the steel-related tasks of the section building and erection processes. However, their workload has shifted in recent years to become increasingly dominated by outfitting tasks. This mismatch further worsens the outfitting-related problems facing these shipyards.

Automatic production planning can potentially mitigate some of the main problems facing European shipyards building complex ships. However, to maximize the effectiveness of such an approach, an integrated method must be created which considers all relevant portions of the shipbuilding process: erection, section building, and outfitting. This dissertation develops an Integrated Shipbuilding Planning Method. This method uses the characteristics of a shipyard, the geometry of a ship, and major project milestones to automatically generate an integrated erection, section building, and outfitting plan. The Integrated Shipbuilding Planning Method was not designed to replace existing shipyard planners, but instead enhance their decision-making abilities. The method aims to provide these planners with a set of high-quality production schedules that can be used as a starting point for drafting the initial plan.

The foundation of Integrated Shipbuilding Planning Method is based on a mathematical model of the shipbuilding process. This model was synthesized from existing literature, expert opinion, and an analysis of the operations of a typical European

shipyard. This model explicitly defines the geometric, operational, and temporal relationships that constrain the shipbuilding process. Novel techniques were developed to automatically extract several of these constraints from the data readily available in a shipyard. The mathematical model also defines the objectives used to measure the quality of a production schedule. A combination of multi-objective genetic algorithms and custom designed heuristics were used to solve the proposed mathematical model. This solution approach tailored historically successful optimization techniques to the specific problem structure of scheduling shipbuilding tasks. Although the developed solution approach does not guarantee that the optimal solution will be found, it allows for sufficiently high-quality solutions to be discovered in reasonable computational times.

The Integrated Shipbuilding Planning Method was evaluated with a test case of a pipelaying ship recently delivered from a Dutch shipyard. This method created a variety of high-quality production plans of both the erection and section building processes in a reasonable computational time. The automatically generated production schedules significantly outperformed those manually generated by the shipyard planners. Especially large gains were seen with respect to the evenness of the outfitting workload and the time available to install components on the slipway. Furthermore, the negligible run time allows planners to quickly make adjustments and test different scenarios. The input data required for creating the section building and erection schedules matches the information that shipyard planners have access to at the start of a new project. Not only was the Integrated Shipbuilding Planning Method able to optimize the planning of the erection and section building independently, it was also shown to be capable of concurrently optimizing the planning of both processes.

Implementing the Integrated Shipbuilding Planning Method in a shipyard for automatically scheduling the section building and erection processes should be relatively straightforward. This method works with the same data (both input and output) as the shipyard planners drafting the initial production schedules. A shipyard would still need to adapt the method to their own process by incorporating their own production data; modifying the constraints and objective to match their production process; tuning the parameters of the solution technique; and implementing the result in the work flow of their planners. However, the global approach and algorithms underlying the solution technique are directly applicable.

A detailed outfitting schedule was also created for the test case ship using the Integrated Shipbuilding Planning Method. Although a high-quality solution was found, the required computational time was somewhat extensive due to the large problem size and complex nature of the relationships constraining the installation of outfitting components. The detailed outfitting schedule was used to determine the influence of the outfitting process on erection and section building. To generate the detailed outfitting schedule, a high level of geometric detail was required because such a schedule is defined on the component level. Such detailed geometry, however, is generally not fully available prior to the onset of outfitting due to the concurrent nature of the detailed engineering and production processes of modern European shipyards. The full implementation of the Integrated Shipbuilding Planning Method for automatically generating detailed outfitting schedules is currently limited by the extensive computational requirements and the timely availability of detailed geometric data.

The Integrated Shipbuilding Planning Method was also used to examine two pro-

duction scenarios to demonstrate its applicability in making strategic decisions. The method was first used to evaluate the performance of three different block building strategies in relation to the erection and section building processes. A recommendation was given for the best strategies assuming the shipyard prioritized having a level resource demand. The effect of the implementation of multi-skilled workers on the outfitting process was also examined. This scenario determined the effect of six different types of multi-skilled mounting teams on the total number of mounting teams required to build the test case ship. In both cases, the scenario analyses provided additional, useful information which could aid a shipyard in making strategic decisions. Because strategic decisions are generally based on historical data, the timely availability of detailed geometric data should not hinder the applicability of the Integrated Shipbuilding Planning Method for supporting such decisions.

The Integrated Shipbuilding Planning Method is novel for several reasons. First, this method is the only automatic planning method developed for shipbuilding that fully incorporates the outfitting process. This method is also the first example of a scheduling methodology that concurrently plans the erection and section building tasks of a shipbuilding project. Furthermore, this approach demonstrates the feasibility of using a priority-based heuristic function in a multi-objective genetic algorithm to effectively schedule a large set of production tasks. Lastly, the production scenarios examined using the Integrated Shipbuilding Planning Method prove that it is possible for a shipyard to use optimization techniques to support strategic planning decisions.

Samenvatting

Europese scheepswerven zijn gespecialiseerd in het bouwen van complexe scheepstypen zoals offshore schepen, jachten, baggerschepen en cruiseschepen. Een markant verschil tussen dit soort schepen en de meer simpele vrachtschepen zoals die in het Verre Oosten gebouwd worden is de hoeveelheid en diversiteit in de uitrusting die benodigd is om het schip zijn taak te laten vervullen. Dergelijke complexe schepen kennen veel technische ruimtes en deze ruimtes kennen een hoge dichtheid aan componenten en equipment. Outfitting is de fase in het scheepsbouwproces waarin de (specialistische) equipment en hulpsystemen (zoals pijpleidingen, kanalen en bekabeling) genstalleerd worden.

De meeste scheepswerven maken geen adequate planning voor het outfitting proces. In de meeste gevallen wordt volstaan met een globale planning waarin aan de betrokken onderaannemers wordt aangegeven binnen welk installatievenster zij hun taken moeten vervullen. Hieruit voortvloeiende conflicten tussen de verschillende belanghebbenden worden besproken tijdens wekelijks overleg. Zon aanpak van outfitting planning wordt gekenmerkt door matige organisatie en communicatie en slecht overzicht. Het outfitting proces op de Europese werven wordt dan ook vaak getroffen door vertraging, rework en sub-optimalisatie. Een schip wordt opgebouwd uit grote stalen blokken die secties genoemd worden. Tijdens het sectiebouwproces worden stalen onderdelen en profielen samengelast tot secties. Aan het einde van de sectiebouw wordt tijd ingeruimd voor het installeren van componenten in een sectie. De scheepsromp wordt opgebouwd door de afzonderlijke secties aan elkaar te lassen, dit gebeurt op een helling of in een dok. Dit samenbouwen wordt aanbouw genoemd.

Europese werven focussen voornamelijk op de planning van de staalbouwgerelateerde taken binnen sectie- en aanbouwprocessen. Desalniettemin is de balans tussen staalbouw en outfitting werk steeds meer richting outfitting werk aan het doorslaan. Dit maakt aan outfitting gerelateerde problemen voor de werf steeds groter. Geautomatiseerde planning van productie kan in potentie sommige van deze problemen verzachten voor de Europese werven die complexe schepen bouwen. Om de effectiviteit van een dergelijke aanpak te maximaliseren moet echter een integrale methode gecreerd worden. Deze methode beschouwt alle relevante onderdelen van het scheepsbouwproces: aanbouw, sectiebouw en outfitting.

In deze dissertatie wordt een Integrale Scheepsbouw Planningsmethode uiteengezet. Deze methode gaat uit van de karakteristieken van een scheepswerf, de geometrie van het schip en hoofd project milestones waarmee automatisch een integrale aanbouw, sectiebouw en outfitting planning gegenereerd wordt. De methode is niet ontwikkeld om de huidige werfplanners te vervangen, maar om hen te ondersteunen bij het ne-

men van kwalitatief beter onderbouwde beslissingen. De methode heeft als doel deze planners te voorzien van een verzameling kwalitatief goede productieplanningen, die als startpunt kunnen dienen voor het maken van een eerste planning door de planners zelf.

De basis van de Integrale Scheepsbouw Planningsmethode is een onderliggend mathematisch model van het scheepsbouwproces. Dit model is de synthese van bestaande literatuur, kennis van experts en een analyse van de operatie van een representatieve Europese werf. Het model omvat een expliciete definitie van de geometrische, operationele en tijdsafhankelijke relaties die het bouwproces bepalen. Er werden nieuwe technieken ontwikkeld om deze relaties automatisch te kunnen extraheren uit de informatie en data beschikbaar op de werf. Het mathematische model beschrijft ook de doelen waaraan de kwaliteit van een productieplanning gerelateerd wordt. Om het voorgestelde mathematisch model te kunnen oplossen werd gebruik gemaakt van een combinatie van multi-objective genetische algoritmen en speciaal ontwikkelde heuristische regels. Alhoewel de ontwikkelde aanpak niet kan garanderen dat de optimale oplossing wordt gevonden, leidt deze wel tot het vinden van voldoende kwalitatief goede oplossingen, binnen een redelijke rekentijd.

De Integrale Scheepsbouw Planningsmethode is gevalueerd met behulp van een testcase: een pijpenlegger schip dat recent is opgeleverd door een Nederlandse werf. De ontwikkelde methode was in staat om een variatie aan aanbouw- en sectiebouwplanningen van hoge kwaliteit te generen, binnen acceptabele rekentijd. Deze automatisch gegenereerde productieplanningen waren significant beter dan de planningen die handmatig opgezet waren. De grootste verbeteringen worden behaald bij het uitvlakken van de outfitting werkbelasting en de tijd die beschikbaar blijft om componenten reeds op de helling te installeren. Bovendien maakt de verwaarloosbare runtime van het model het mogelijk om snel aanpassingen op de planning te maken en verschillende alternatieve scenarios te genereren en vergelijken. De benodigde inputgegevens om deze sectiebouw en aanbouw schemas te creren komt overeen met de informatie die planners normaalgesproken beschikbaar hebben bij de start van een nieuwe project.

De Integrale Scheepsbouw Planningsmethode was niet alleen in staat om de planning van zowel aanbouw als sectiebouw onafhankelijk van elkaar te verbeteren, maar ook om gelijktijdig de planning van beide processen te optimaliseren. Het implementeren van deze Integrale Scheepsbouw Planningsmethode voor het automatisch genereren van sectiebouw en aanbouwplanningen lijkt redelijk simpel te zijn, aangezien de methode gebruik maakt van dezelfde data die planners nu ook al gebruiken bij het maken van een initile productieplanning. Een scheepswerf zou de methode aan haar eigen proces aan moeten passen door de gebruikte productiedata in het model aan te passen, de randvoorwaarden en doelfuncties in het model te laten aansluiten op het eigen productieproces en ook de parameters af te stemmen op de specifieke omstandigheden. Het resultaat hiervan zou gemplementeerd moeten worden in de normale werkwijze van de planners. Echter, de globale aanpak, de oplossingstechniek en de onderliggende algoritmen zijn direct toepasbaar.

The Integrale Scheepsbouw Planningsmethode werd ook gebruikt om een detailoutfitplanning te genereren voor het test schip. Alhoewel in dit geval een oplossing van hoge kwaliteit werd gevonden, was de vereiste rekentijd substantieel, gezien de omvang van het probleem en de complexe aard van de relaties die het outfitting proces bepalen.

Deze detail-outfitplanning werd gebruikt om de invloed van het outfitting process op aanbouw en sectiebouw te kunnen bepalen. Om de detailplanning te kunnen genereren was een voldoende gedetailleerd geometrisch model nodig, want zon planning wordt op het detailniveau van de componenten bepaald. Een dergelijk gedetailleerd model is echter normaalgesproken niet volledig beschikbaar voordat de outfitting gaat beginnen; dat is het resultaat van de overlap tussen detail-engineering processen en productieprocessen, zoals die gewoonlijk bestaat op een moderne Europese werf. Om dit moment wordt een volledige implementatie van de Integrale Scheepsbouw Planningsmethode beperkt door de vereiste uitgebreide rekenkracht en de tijdige beschikbaarheid van voldoende gedetailleerde geometrische data.

Om de toepasbaarheid van de Integrale Scheepsbouw Planningsmethode voor het nemen van strategische beslissingen te demonstreren, werd de methode ook gebruikt om twee productiescenarios te onderzoeken: Eerst werd de methode gebruikt om de performance van drie verschillende blokbouw-strategien in relatie tot aanbouw en sectiebouw processen te evalueren. Onder de aanname dat de werf prioriteit gaf aan een zo vlak mogelijke resource capaciteitsvraag, werd een aanbeveling gedaan voor de beste bouwstrategie. Ook werd het effect van multi-skilled personeel op het outfitting proces onderzocht. Dit scenario bepaalde het effect van zes verschillende typen multi-skilled installatieteams op het totaal aantal benodigde teams over de bouw van het test case schip.

In beide gevallen voorzagen de gemaakte analyses in aanvullende, nuttige informatie die een werf zou kunnen helpen bij het nemen van strategische beslissingen. Omdat strategische beslissingen normaalgesproken op historische data gebaseerd worden, zou voor deze toepassing de tijdige beschikbaarheid van gedetailleerde geometrische data geen belemmering voor de toepasbaarheid van de Integrale Scheepsbouw Planningsmethode mogen zijn. De Integrale Scheepsbouw Planningsmethode is vernieuwend en wel om de volgende redenen: Allereerst is deze methode de enige -voor de scheepsbouw ontwikkelde- automatische planningsmethode die ook het outfit proces omvat. Verder is deze methode het eerste voorbeeld van een planningsmethode die gelijktijdig de aanbouw en sectiebouw van een project plant. Deze aanpak laat ook zien dat het haalbaar is om priority-based heuristic function in een multi-objective genetisch algoritme toe te passen om een grote set productietaken effectief te kunnen plannen. Tenslotte bewijzen de productiescenarios zoals die onderzocht werden met de Integrale Scheepsbouw Planningsmethode dat het voor een werf mogelijk is om optimalisatietechnieken in te zetten om strategische planningsbeslissingen te kunnen ondersteunen.

Chapter 1

Introduction

The shipbuilding industry is strategically important for Europe. This industry provides a means of transport for international trade, supplies modern navies with capable and effective ships, and generates advanced technology spin-offs for other industries (LeaderSHIP 2015, 2003). In recent years, shipbuilding has proven to be an efficient and technologically advanced segment of European manufacturing which is capable of driving growth and creating jobs (LeaderSHIP 2020, 2013). In 2013, the European shipbuilding industry and its suppliers employed roughly 500,000 people (SEA Europe, 2014).

Up until the middle of the 20th century, Europe dominated the shipbuilding industry. However, in the last 50 years the shipbuilding market share has continuously shifted to Far East shipbuilding nations (Mickeviciene, 2011). China, South Korea, and Japan currently represent 39%, 30%, and 23% of the global orderbook by deadweight while European yards only account for 2.7% (Shibuilder's Association of Japan, 2015). This shift occurred due to the economic growth of Far Eastern nations, government interventions, and lower wages. Lower labor costs are particularly important, as these costs account for roughly 20% of a ship's cost (ECORYS, 2009). European countries have significantly higher labor cost than the Far East shipbuilding nations. Hourly compensation rates in Europe are roughly 2000%, 200%, and 133% of those in China, South Korea, and Japan, respectively (Conference Board, 2014). Not only are labor costs in Europe extremely high, tough labor policies in European shipbuilding countries (especially Germany, Italy, Spain, and the Netherlands) make it costly and difficult to adjust workforce size to meet varying demands (Schank et al., 2005).

As a result of this strong cost competition, European shipyards have increasingly focused on building high value-added, complex ships (Müller, 2007). Labor costs are much less important for these ships (ECORYS, 2009). European shipyards are also generally smaller than shipyards in the Far East for historical reasons (LeaderSHIP 2015, 2003), making it even more difficult for European shipyards to compete while constructing simple ship types (Mickeviciene, 2011). A majority of the portfolio of European shipyards now contains complex ships, such as cruise, passenger, offshore, dredging, naval, yachting, fishing, and research ships. Figure 1.1 shows the orderbook of European shipyards from 2003 to 2014. This figure shows that the orderbook of European shipyards has become increasingly dominated by complex ships in recent

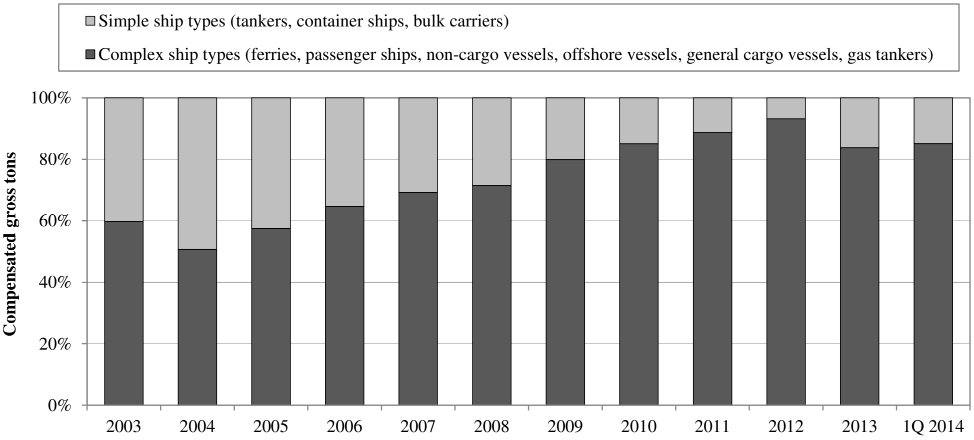

Figure 1.1: Orderbook of European shipyards, adapted from SEA Europe (2014)

years, and these ships currently account for over 85% of the orderbook. Although European shipyards will build less than 3% of new ship orders by deadweight, these orders represent 12% of the global market share due to the high-value of complex ships.

The European shipbuilding industry faces several key challenges to maintain a dominant position in the specialized ship market. First, other shipbuilding nations, such as China, are beginning to shift their shipbuilding strategy to focus more heavily on the construction of complex ships (Mickeviciene, 2011). This push into the specialized ship market has partly occurred due to an overcapacity in the cargo shipping fleet caused by a pre-crisis speculative boom in 2008 (LeaderSHIP 2020, 2013). Moreover, new competitors in nations such as Vietnam, India, Turkey, the Philippines, Brazil, and Russia are also entering the shipbuilding industry (Mickeviciene, 2011). European shipyards must also continuously adapt and innovate their specialized ship designs to meet the technical challenges of developing industries, such as harvesting offshore energy. Furthermore, ships must continue to meet increasingly stringent environmental regulations (LeaderSHIP 2020, 2013). Fortunately, European shipyards are generally more flexible with respect to the adaptation of innovation due to their smaller size (Mickeviciene, 2011).

Complex ships contain many specialized systems that require special expertise to develop, construct, and install (Maffioli et al., 2001), differentiating the production of complex ships from that of the simpler ship types. Upwards of 50,000 components can be installed on a modern complex ship (Wei et al., 2010). The installation of these components is referred to as outfitting. Common outfitting tasks include the mounting of pipes, cable trays, ducting, and equipment. Other non-steel related production tasks, such as painting and installing insulation, are also considered to be outfitting. At least 70% of a modern, complex ship's value comes from outfitting (LeaderSHIP 2020, 2013). In the future, the value and complexity of these ships will continue to increase, as seen in the offshore sector (CESA, 2011). Complex ship owners usually request ships custom built to meet their specific needs. As a result, these ships are typically one-of-a-kind orders or built in a very short series (LeaderSHIP 2020, 2013). Because European shipyards continue to focus more on the construction of complex ships, the relative importance of steel work is increasingly less compared to outfitting. Substantial gains can be achieved by these shipyards by improving the outfitting process. This is especially true as the complexity of these ships increases (Wei, 2012).

European shipyards have evolved in the past decade to become optimized for the construction of complex ships. Many of these yards extensively use subcontractors for outfitting tasks that were traditionally performed in-house, such as the installation of equipment, pipe spools, cable trays, and HVAC (heating, ventilation, and air condition) ducts (Wei, 2012). IKEI (2009) contains a detailed list of tasks commonly outsourced. European shipyards use subcontractors for several reasons. It allows a shipyard to reduce fixed costs and respond to the cyclical nature of the industry, especially in the face of tough labor policies (Müller, 2007). Using specialized subcontractors also allows a shipyard to focus on its core competencies while providing a higher quality product (Schank et al., 2005). In addition to extensively using subcontractors, the time between an order and delivery at a European shipyard is typically very short. As a result, a large number of tasks must be performed in parallel and the ship's construction starts before the design is complete (Wei, 2012).

1.1 Problems with Outfitting

Even though European shipyards specialize in building outfitting-intensive ships, the outfitting process is one of the most problematic for these shipyards. These problems stem from the fact that the production planning of these shipyards is still heavily focused on steel-related shipbuilding tasks. A shipyard defines rough time windows during which subcontractors can install components in certain areas, and weekly meetings are used to deal with the daily unexpected interferences of outfitting. This type of approach is insufficient for spaces densely packed with components (Wei, 2012). This section describes some of the key challenges facing European shipyards related to outfitting.

Lack of organization

The planning of the outfitting process is plagued by a lack of organization. This problem is magnified by the sheer number of stakeholders involved in outfitting. For example, the installation of a boiler can require upwards of 11 different parties (Wei, 2012). To successfully install a component, the correct material, equipment, and personnel must be in the right place at the right time. Poor logistics can be extremely costly to outfitting. Wei (2012) observed that it took a pair of workers 35 minutes to find and dig out a pipe spool from the bottom of a pallet which had been delivered to a work site. If the pipes had been initially sorted based on installation sequence, this work would have been avoided. However, the current outfitting planning methods do not allow for this type of organization. Improving the organization of different subcontractors is very difficult since the party coordinating their efforts must have a good understanding of each subcontractor's work (Olsson, 1998). This challenge is amplified by the long communication chain which exists when multiple layers of subcontractors are present (Tam et al., 2011).

Delays and rework

Because the outfitting process is planned and executed independently by each subcontractor, it is often affected by interferences and disturbances. These frequently result in delays and rework on the work site (Wei, 2012). Rework can increase the production cost by up to eight fold since the repair work must often be performed during a less ideal time in the production process (Rubesa et al., 2011). For example, installing a component in a crowded machinery space while a ship is moored at the quay is significantly more challenging than performing the same task in a relatively open section in a workshop. Because the work of the different subcontractors is highly interdependent, delays and rework experienced by one subcontractor will greatly reduce the ability of others to complete their work on time (Müller, 2007). These problems often result from poor outfitting planning. For example, Wei (2012) describes an example of the collision between a steel pipe and cable tray support, a common problem seen in European shipyards. The resulting rework could have been avoided if both contractors had been better aware of each other's tasks.

Sub-optimization

Another problem negatively affecting the outfitting process is sub-optimization. This process is vulnerable to sub-optimization due to the large number of subcontractors, which often work autonomously and are primarily focused on fulfilling their own obligations. This often results in the subcontractors protecting their own interests instead of working for the good of the overall project (Olsson, 1998). Furthermore, Caprace et al. (2011) find that the quality of outfitting schedules manually produced by an experienced manager were generally not optimal. Wei (2012) presents an example of sub-optimization in the outfitting process, where two workers are forced to install an HVAC duct in an awkward position because the cable trays above the duct had already been installed. This sub-optimization partially results from a lack of transparency, as each subcontractor works from their own plans independently. The limited communication between subcontractors is often informal and not extensively documented, making it very difficult to manage the process (Wei, 2012).

Loss of industry specific knowledge

Another problem of European shipyards is the loss of industry specific knowledge. This is especially important for outfitting since outfitting needs well-educated and highly skilled workers. Outfitting work requires the ability to visualize complex 3D shapes and spaces using only 2D drawings. Furthermore, this work is often ambiguous and relies heavily on tacit knowledge (Wei, 2012). It usually takes five years for someone to acquire the necessary experience to be considered a skilled employee in shipbuilding ('t Hart and Schotte, 2008). A significant loss of skill will occur within European shipbuilding due to the age structure of the sector (Granger, 2008). This problem has been recently exacerbated by the heavy reliance of European shipyards on outsourcing, since they have not recruited a sufficient number of new employees and outsourcing also hampers the natural transfer of industry specific skills to the next generation of employees (Müller, 2007). Workforce migration (Granger, 2008) and the increased complexity of the ships which are being built (LeaderSHIP 2020, 2013) further worsen this problem.

Lack of mathematical definition

A lack of mathematical definition also exists for the outfitting process. To date, very limited work has been performed to develop the mathematical dependencies and relationships that govern outfitting. The research that has been conducted generally considers a simplified version of the process. This lack of mathematical definition leads to a lack of outfitting scheduling knowledge. Even though a vast body of scheduling knowledge exists in the fields of classical optimization, operations research, and the steelwork portion of the shipbuilding process, almost no work has been done in the field of outfitting scheduling.

1.2 Automatic Production Planning

Automatic production planning is a method which generates a schedule for a production process using a computerized algorithm. In the case of outfitting, such a schedule would indicate the location, time, and personnel associated with the installation of each component. This is done by first creating a series of constraints which must be satisfied. Next, an algorithm is used to find an optimized schedule based on an objective function, such as minimizing man-hours, balancing workload, or maximizing the ease of installation. Automatic production planning of outfitting has the following advantages (Wei, 2012):

- Gives a realistic baseline schedule for production which can be used to track current progress and improve the management of the process
- Considers all of the complex interdependencies of a process, even if there are too many for the most experienced planner to take into account
- Finds the best schedules for situations which have too many variables and possible arrangements for a human to successfully optimize
- Provides a good estimate for the throughput time and resource requirements
- Breaks a larger process into smaller tasks that are easier to control
- Reduces risks and uncertainties

A fairly developed attempt at the automated detailed scheduling of the outfitting process of European shipyards was completed by Wei (2012). Her work already laid much of the required groundwork, such as industry observation, data gathering, and demonstrating feasibility. However, Wei concluded that her work could not be directly used by the European shipbuilding industry because it failed to include the effects of the erection and section building process. Section building is the process of constructing the large steel blocks which compose the hull of a ship, and erection is the process of assembling those blocks together to form the ship's hull. These two processes dictate during what time periods a shipyard is able to perform outfitting in each space. Therefore, it is necessary to generate the production schedules of the erection and section building process concurrently with outfitting to fully capture the interactions between the three processes.

Creating an integrated erection, section building, and outfitting plan could potentially reduce or eliminate the problems currently affecting the outfitting process of European shipyards. Having a centralized outfitting plan available at the beginning of the outfitting process helps alleviate the lack of organization and lack of transparency common to outfitting work. This plan can be used as a centerpiece for communication between the shipyard and subcontractors to ensure that each party understands which tasks should be completed at what times. This, in turn, should reduce the amount of delays and rework. The problem of sub-optimization is also addressed since the integrated production plan would be created by a method that seeks to optimize the process globally, instead of being biased towards the needs of the shipyard, owner, or any subcontractor. Codifying the experience and rules of thumb of a manufacturing process also makes the tacit knowledge of those processes explicit. This mitigates the loss of industry specific skill and therefore works to solve the problem of an ageing workforce present in European shipyards. The erection, section building, and outfitting processes must be mathematically defined to automatically generate an integrated production plan. Furthermore, the currently available scheduling knowledge must be expanded and tailored to efficiently solve these definitions. This will address the lack of mathematical definition and scheduling knowledge of the outfitting process.

1.3 Research Objectives and Scope

The previous sections describe the current state of the European shipbuilding industry, specifically the recent shift in the order portfolios of shipyards to focus on the construction of complex ships. Complex ships differ from simple cargo ships because they are densely packed with specialized systems, each of which must be designed and installed. Overall, this shift has had an adverse effect on the production processes of these shipyards since they were not accustomed to building outfitting intensive ships. These effects include delays, rework, and sub-optimization, and their impact is worsened by an aging workforce and a lack of theoretical knowledge of the outfitting process. The conclusion was drawn that the problems facing the European shipbuilding industry might be partially addressed by developing an integrated method for automatically planning a shipyard's production process. However, such a method has yet to be developed. Therefore, the first research question of this dissertation addresses the feasibility of such an approach.

> **Research Question #1:** Is it possible to develop a method for automatically generating an integrated erection, section building, and outfitting plan for European shipyards building complex ships?

Several challenges threaten the successful development of such an automatic planning method. The first is the sheer size and computational complexity of the problem. Scheduling problems are among the most difficult of classical optimization problems. Furthermore, many scheduling algorithms found in literature are incapable of finding solutions in a reasonable computational effort for problems with upwards of 50,000 tasks, as is required to schedule the outfitting process of complex ships. Sufficient availability and access to data also threaten the development of such a planning method. Shipyards do not always record the necessary data. Moreover, subcontractors are not always willing to freely share information with shipyards regarding the man-hours required to complete tasks since this information is used by both parties when negotiating contracts. Once it has been established that it is possible to automatically create a feasible production schedule in a reasonable computational time, the usefulness of such a schedule must be assessed. This is done by the second research question.

> **Research Question #2:** How can developing such an integrated planning method benefit these shipyards?

The second research question is further defined by two subquestions.

> **Research Subquestion #2.1:** How do the integrated production plans created automatically by the developed method compare to those manually created by shipyard planners?

> **Research Subquestion #2.2:** How can the developed automatic planning methodology be used to improve the production process of these shipyards?

The first subquestion addresses the quality of the production schedules produced by the automatic production planning method. If the method does not produce schedules of at least comparable quality to those currently being used, shipyards will not implement such a method. Such a comparison can only be made for the section building and erection processes, since detailed outfitting schedules are not typically created by the planners of contemporary European shipyards.

The second subquestion examines the applicability of the developed method beyond the creation of production schedules. This method could also support a shipyard when making strategic decisions, such as the selection of a block building strategy or the investment in multi-skilled outfitting workers. Shipyards often make such decisions using very limited data out of necessity since no better data is available. The developed method could generate some of the missing data required to help support some of these strategic decisions.

This dissertation focuses on the automatic generation of production schedules for ship production. This approach is one of the most promising directions for improving the shipbuilding process of European shipyards. As a result, this research relies on the data available at the time the research was performed. The best estimation methods found in literature were implemented when data was not available. This allows the main focus of this research to be on the development of the method instead of on data collection. However, recommendations are given for what types of missing data are most beneficial to collect in the future.

This research examines the production processes with the highest impact: erection, section building, and outfitting. The influence of processes which support erection, section building, and outfitting is not considered in this dissertation. These processes include those which supply the necessary materials and information, such as procurement, part fabrication, and engineering. As long as these processes are operating smoothly, they do not hinder the erection, section building, and outfitting of a ship. In this research, outfitting is also limited to tasks which have the greatest interdependencies with erection and section building.

Lastly, the focus of this dissertation is on the shipbuilding process, not the design of the ship being built. Therefore, the ship design is taken as an input, allowing this research to be generally applied to shipyards regardless of the ship owner's requirements and decisions. As a result, the possibility of varying this design to improve the production process is not considered. The potential benefits of design for production, such as those examined by Rigterink et al. (2013) and Kolic et al. (2010), are not considered.

1.4 Research Approach

Initially, the erection, section building, and outfitting processes of European shipyards were examined to determine the constraints and objectives which drive these processes. This was done by reading literature, observing the process, and consulting experienced shipbuilding personnel. The graduation project of Gregory (2015) was also used to gather additional information about the outfitting process which was not previously available.

The driving constraints and objectives of each process were used to develop three separate mathematical models. Independent methods were developed for solving each of these models: the Erection Planning Method, Section Building Planning Method, and Detailed Outfitting Planning Method. These three methods were then combined together to form the Integrated Shipbuilding Planning Method. To demonstrate that the Integrated Shipbuilding Planning Method satisfies the first research question, a test case was performed focusing on a pipelaying ship recently delivered from a Dutch shipyard. The Integrated Shipbuilding Planning Method can be thought of as a virtual laboratory, and the test case as an experiment performed within that laboratory. The production schedules created for the test case ship were all individually verified and their feasibility was assessed. The quality of the production schedules created by the Integrated Shipbuilding Planning Method for the test case ship was compared to the schedules manually created by shipyard planners where possible. In this way, the experiment within the virtual laboratory was used again to answer the first sub-question of the second research question.

To answer the last sub-question, two different strategic decisions that European shipyards potentially face were analyzed. The first of these was the selection of a block building strategy. Because the block building process lies at the intersection of the erection and section building processes, it was necessary to create a Combined Erection and Section Building Planning Method to examine this scenario. The second scenario analyzed was the implementation of multi-skilled workers. This scenario required the Detailed Outfitting Planning Method. Again, a virtual experiment in terms of a test case ship was used to determine if the Integrated Shipbuilding Planning Method can be used to help shipyards improve their operations.

1.5 Dissertation Structure

This dissertation consists of nine chapters. The first chapter, the introduction, gives an overview of the current state of the European shipbuilding industry and highlights one of the main problems facing this industry. An approach to address this problem is introduced and research questions are formulated to assess the feasibility and applicability of the approach. This chapter also contains the limitations to the scope of the research.

Chapter 2 provides some relevant background. This chapter includes a description of the European shipbuilding process as well as a description of the production plans used by shipyards to manage this process. A literature review of the automatic production planning in the shipbuilding industry is also presented.

The third chapter introduces the Integrated Shipbuilding Planning Method developed by this dissertation. This method is composed of three methods, which plan the erection, section building, and outfitting processes of shipbuilding. The development and assessment of the Erection Planning Method, Section Building Planning Method, and Outfitting Planning Method is addressed by Chapters 4, 5, and 7 respectively. Chapter 6 combines the Erection Planning Method and Section Building Planning Method to create a Combined Erection and Section Building Planning Method.

Chapter 8 applies the method developed in the previous five chapters to analyze two different shipbuilding scenarios. The first uses the Combined Erection and Section Building Planning Method to assess several block building strategies and the second uses the Outfitting Planning Method to examine the effect of introducing multi-skilled outfitting workers.

Chapter 9 contains the conclusions and recommendations. This chapter reflects on the suitability of the developed method for answering the research questions posed in the first chapter and discusses the limitations of this research. Furthermore, this chapter presents recommendations for both future research and for shipyards interested in improving their production process through automatic production planning.

Chapter 2

Background*

This chapter provides some background information to support this dissertation. The shipbuilding process of European shipyards building complex ships is described to clarify which processes are considered. The current planning practices of these shipyards are also described in detail. The method developed in Chapters 3 through 7 seeks to emulate and improve on these practices. Furthermore, this chapter defines the terminology which will be used in the remaining chapters. Lastly, a review is presented of automatic planning literature and its relationship to shipbuilding. This review describes the underlying principles which inspired the methods used in this research and positions this dissertation in the broader research community.

2.1 Shipbuilding Process

This section provides a general overview of the shipbuilding process of European shipyards building complex ships. The purpose of this section is not to fully describe this process, but instead to create a set of definitions which are used throughout the remainder of the dissertation. A more detailed description of shipbuilding can be found in Eyres and Bruce (2012), Colthoff (2009), Vlaar (2010), Wei (2012), and Gregory (2015). The first three of these works focus on the steel-related aspects of shipbuilding, and the last two focus on outfitting.

Figure 2.1 shows the main stages required to construct a complex ship. Stages that are outside the scope of this dissertation (such as the specification of requirements, procurement, part fabrication, commissioning, sea trials, and delivery) are excluded. The stages shown in Figure 2.1 are listed in the order in which a portion of a ship experiences the production process. However, many of these stages occur in parallel for different parts of the ship. For example, production generally begins for the first section soon after the design of that section is completed. Furthermore, the first four production stages occur once per section, yet sections are erected in a sequential order. This means that these four stages are executed concurrently throughout a majority of the production process. Figure 2.2 illustrates the main activity which is performed during each stage of the shipbuilding process.

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*This chapter is partially based on Rose and Coenen (2015b, 2016b).

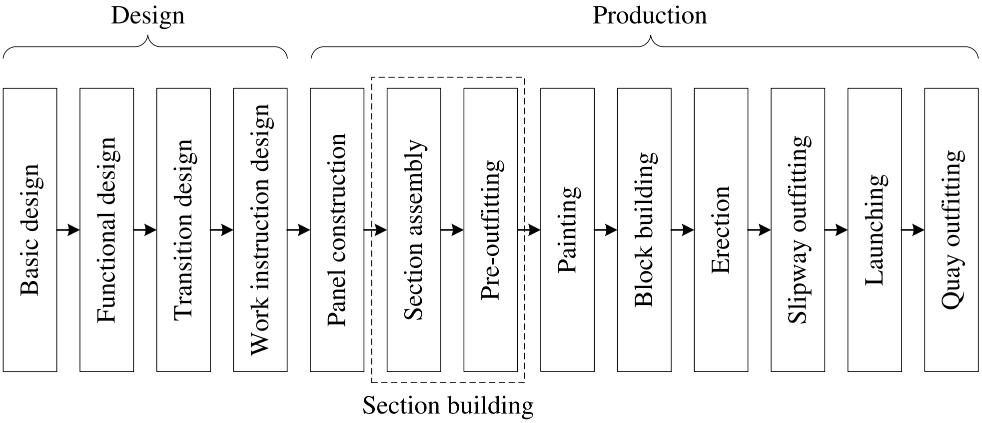
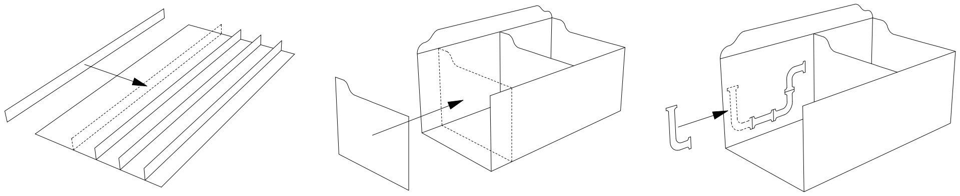
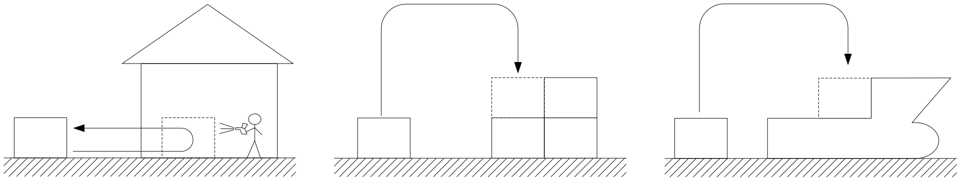


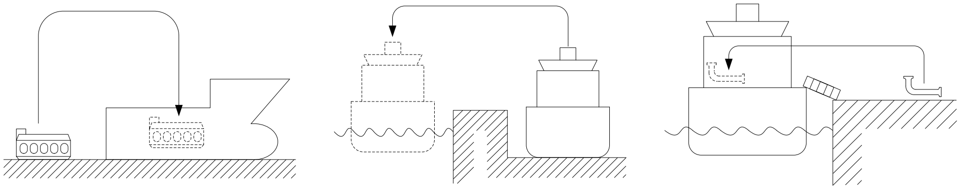
Figure 2.1: Stages of the shipbuilding process



(a) Panel construction **(b)** Section assembly **(c)** Pre-outfitting



(d) Painting **(e)** Block building **(f)** Erection



(g) Slipway outfitting **(h)** Launching **(i)** Quay outfitting

Figure 2.2: Main activity of each shipbuilding stage

2.1.1 Design

The first set of shipbuilding stages cover the design of complex ships. Because complex ships are typically one-off orders or built in very short series, a significant amount of engineering work must be performed for each new project. There exists a variety of different ship design stage definitions in literature. The design stage definitions of Storch et al. (1995) are used in this dissertation as these authors focus specifically on shipbuilding.

Basic design: During this stage, the ship is described as a total system. An initial solution is specified through creating a preliminary general arrangement and selecting the materials and technologies to be used (hull form, propulsion systems, mission equipment, etc.). This stage is also referred to as conceptual or preliminary design, and authors focused on the design process tend to split basic design into several sub-stages.

Functional design: Each of a ship's systems are schematically defined during this design stage. These diagrams are used to create required material lists for each system and to acquire owner and regulatory approval.

Transition design: During this stage, a ship's design is reorganized from system schematics to a design based on physical location (such a sections, blocks, zones, etc.). The purpose of transitional design is to make the function design suitable for work instruction design.

Work instruction design: This stage makes the ship design suitable for production. This is accomplished by determining the arrangements, dimensions, and other specifications of all individual parts. Detailed cost estimations and construction drawings are produced during this design stage. Other authors sometimes combine this stage with transition design to form a single stage referred to as detail design or engineering.

2.1.2 Production

The remaining shipbuilding stages shown in Figure 2.1 cover the production of a ship. The purpose of production is to build the ship design created during the engineering stages. Production stages are divided into two groups: those related to constructing a ship's hull and those related to outfitting. The following hull-related stages are included in the shipbuilding process:

Panel construction: Panels are produced during this stage, where a typical panel is composed of several steel plates butt-welded together stiffened by profiles, girders, and brackets.

Section assembly: During section assembly, sections are built by welding together panels and individual parts. A section is the basic construction unit of a ship, where a typical complex ship is composed of 50-200 sections.

Block building: In some cases, several sections are welded together to form blocks prior to erection.

Erection: This stage involves assembling the sections and blocks of a ship on a slipway/drydock to form the hull. For the remainder of the dissertation, it is assumed that a slipway is used. The sections and blocks are then welded together during erection.

Launching: During this stage the ship is moved from the slipway to the quay. The hull must be watertight prior to launching, and all external underwater work should be completed.

The shipbuilding process contains the following outfitting-related stages:

Pre-outfitting: Components are mounted to sections in the section assembly area during the pre-outfitting stage. This is done while the sections are still being assembled or after section assembly is complete prior to painting the section.

Painting: After a section is assembled and the necessary pre-outfitting is completed, the section is moved to a paint hall to be painted.

Slipway outfitting: Components are installed in the partially-erected ship on the slipway during this stage. It is only possible to use a crane to assist with installing large items while the section composing the ceiling of the room containing the item has not yet been erected.

Quay outfitting: This stage involves installing components in the ship while the ship is moored alongside the quay. At the conclusion of this stage, all components should be installed.

One additional stage shown in Figure 2.1 is section building, which refers to the time a section spends in the section building hall. A section is in the section building hall while it is either being assembled or pre-outfitted.

2.1.3 Outsourcing

Outsourcing is an integral part of the production process of many contemporary European shipyards (Wei, 2012). Work can be shifted from the shipyard to subcontractors in two ways. First, a shipyard can outsource the installation of entire systems or disciplines, such as piping or the electrical system. This type of outsourcing, known as total outsourcing, allows the shipyard to focus on its core competencies while providing a higher quality product (Schank et al., 2005). Outsourcing the installation of systems is especially beneficial when building complex ships because it is costly to develop each of the skills required to install all the necessary sophisticated systems in-house. Subcontractors hired to install these systems perform their work at the shipyard while the ship is being constructed.

The second type of outsourcing, peak outsourcing, occurs when a shipyard temporarily increases its capacity through subcontractors (Schank et al., 2005). For example, European shipyards often outsource portions of the section building process. In this case, sections are built off-site and delivered to the shipyard prior to erection. Peak outsourcing is done when the capacity requirements of a project exceeds the capacity available at a shipyard, yet the shipyard does not want to invest in expanding their facilities.

2.1.4 Other Shipbuilding Strategies

The shipbuilding process described in the previous sections closely mirrors that of Royal IHC, a Dutch shipbuilding group. Royal IHC is the shipyard selected for the test cases presented in this dissertation because their shipbuilding process is typical of many European shipyards building complex ships. This process represents a flexible, balanced approach that can easily be adjusted to meet market conditions through changes in outsourcing strategy. However, other shipbuilding strategies exist for European shipyards.

One of the most innovative shipyards in Europe is Meyer Werft's facility in northern Germany (Meyer Werft, 2015). Meyer Werft is an industry leader in the construction of large cruise ships. This shipyard is separated from many other European shipyards by their strategic decision to in-source as much of the production process as possible. For example, the shipyard produces most of the required pipe spools in-house using a semi-automated pipe production facility. Even though this direction prevents Meyer Werft from reaping the benefits of outsourcing, it gives the shipyard much greater control over their own production process. This benefit is seen in their section building process, where sections are produced on a large conveyor belt in a process resembling an assembly line.

Other shipyards have chosen to outsource the entire erection process. This strategy used by small Norwegian shipyards. These shipyards have taken advantage of the cheap labor found in Eastern European countries to inexpensively construct the hulls of their ships. This allows shipyards to completely focus on the core competencies: the coordination of the installation of sophisticated systems. However, these shipyards have much less control over their pre-outfitting process, making it difficult to obtain a high pre-outfitting percent. As a result, some of these yards have begun in-sourcing the production of the most complex sections, such as the main engine room sections (Holte and Moen, 2010).

A similar strategy has also been pursued by Damen Shipyards in the Netherlands. Initially, Damen Shipyards began buying ship hulls from Poland. Eventually, they acquired shipyards in Poland, Romania, China, and Singapore. Over time, these yards gradually transformed from facilities building ship hulls to ones capable of building entire ships. For Damen Shipyards, pursuing this strategy of outsourcing major portions of the shipbuilding process reduced production costs at the expense of additional engineering activities. This strategy also shifted the work done by the shipyard from production activities towards organizing, orchestrating, and supporting tasks (Berghuis and Den Butter, 2013).

2.2 Shipyard Planning in Practice

This section discusses the planning process typical of European shipyards building complex ships. The contents of this section are a summary of Meijer (2008), Colthoff (2009), Wei (2012), and Gregory (2015), who provide detailed insight into contemporary European shipyard planning. Figure 2.3 presents a chronological overview of the different planning levels performed.

The Master Plan is created at a very early stage in a project, during basic design. This plan is typically produced prior to contract signing. The Master Plan contains

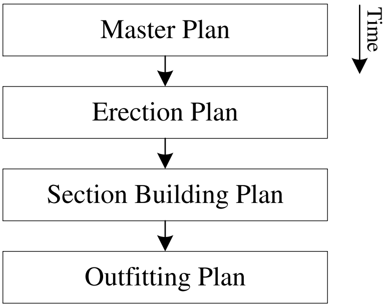


Figure 2.3: Overview of shipyard planning levels

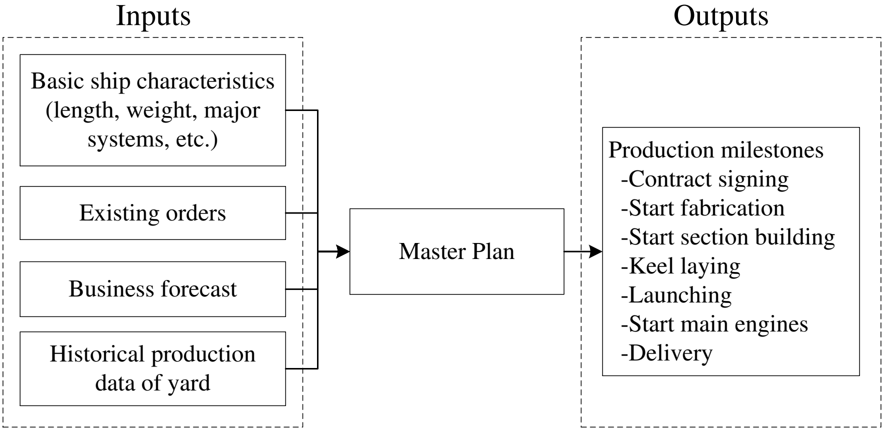


Figure 2.4: Inputs and outputs of the Master Plan

the completion dates of key milestones in the shipbuilding project, such as contract signing, keel laying, launching, and delivery. These milestones are included in the contract, and payments from the owner to the yard are associated with their completion. This plan also indicates how a shipbuilding project interacts with the previous and following project in terms of global shipyard resource requirements. Because the Master Plan is created early in the engineering process, a shipyard works with a fairly limited ship design when making this plan. Therefore, a shipyard relies on historical data, estimation methods, and expert judgment to create the Master Plan. Figure 2.4 shows the information available when creating a Master Plan and the typical contents of this plan.

The second planning level is the creation of the Erection Plan. A shipyard generates the Erection Plan sometime during the end of transition design or in the beginning of the work instruction design. This plan determines the time each section is erected on the slipway. The slipway is a strategic resource for European shipyards because it typically limits a shipyard's throughput. Furthermore, unlike section building, it is not possible to gain additional slipway capacity through outsourcing. A shipyard avoids delaying the Erection Plan whenever possible, as doing so implies the following

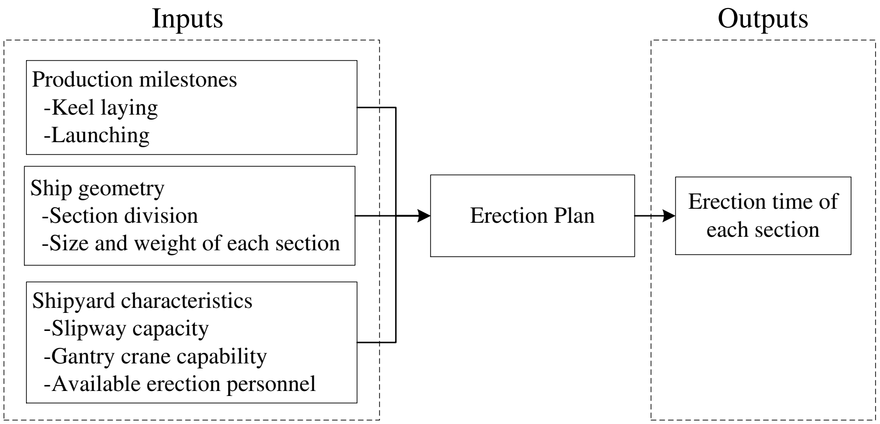


Figure 2.5: Inputs and outputs of the Erection Plan

project will also be delayed. Figure 2.5 outlines the information typically used to create an Erection Plan and its contents. Chapter 4 contains a more detailed description of this plan.

After the Erection Plan is completed, the shipyard creates the Section Building Plan. This generally occurs at the start of work instruction design. This plan indicates when each section should be assembled and pre-outfitted. The Section Building Plan is generated by extrapolating backwards from the Erection Plan to ensure that each section is ready to be erected on time. The number of sections that can be built simultaneously is limited by the floor area of the section building hall. Whenever the section building requirements of a shipyard exceed its own capacity, the production of entire sections is outsourced. It is also common for shipyards to only consider pre-outfitting on a rudimentary level when creating the Section Building Plan. For example, each section may be assigned two weeks for pre-outfitting regardless of the required outfitting work. For each section the pre-outfitting process is given some overlap with the section assembly process (usually around one week). This allows for the installation of components which are easier to mount before the entire section is fully assembled, such as double bottom pipes. The inputs and outputs of the Section Building Plan are shown in Figure 2.6. A more detailed description of this plan is found in Chapter 5.

A detailed Outfitting Plan on the component level is not created by the shipyard. Instead, the shipyard uses the Section Building Plan to indicate to the subcontractors when each section is available for pre-outfitting. The Erection Plan also contains the time period available for slipway outfitting. Similarly, the painting schedule indicates the latest point in time hotwork can be performed in a space. Subcontractors independently maintain their own schedules. A weekly meeting is conducted with representation from each of the outfitting subcontractors and the shipyard. During these meetings, the subcontractors and shipyard determine what outfitting will be performed during the upcoming week, resolve conflicts between subcontractors, and make minor adjustments to the Section Building Plan.

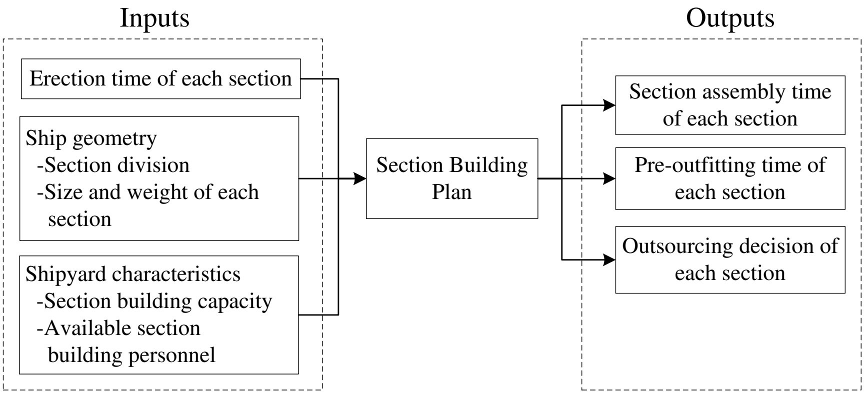


Figure 2.6: Inputs and outputs of the Section Building Plan

2.3 Automatic Planning

The following section provides a broad literature review of automatic planning and its position in the shipbuilding industry. Initially, a brief overview of theoretical scheduling is given, with a focus on the techniques used to automatically produce production schedules. The implementation of such techniques is then examined in manufacturing processes. Finally, the current state of the implementation of automatic planning methods in the shipbuilding industry is reviewed in the context of the previously examined topics.

2.3.1 Theoretical Scheduling

In the past few decades, a large research effort has been conducted globally to solve idealized, theoretical optimization problems. These classical optimization problems include several focused on scheduling, such as parallel machine scheduling (Cheng and Sin, 1990), the resource constrained project scheduling problem (Brucker et al., 1999), job-shop scheduling (Blazewicz et al., 1996), and the resource availability cost problem (Möhring, 1984). These scheduling problems can be adapted to resemble many real life processes. For example, Allahverdi et al. (1999) reviews the addition of different setup time conditions to a variety of scheduling problems. Hartmann and Briskorn (2010) survey and categorize the different variations of the resource constrained project scheduling problem, including temporal constraints (time lags, deadlines, etc.), resource constraints (renewable, non-renewable, cumulative, etc.), and objectives (time, resources, cost, etc.).

A wide variety of different solution approaches have been proposed by the optimization community to solve these scheduling problems. These are broadly classified as either exact methods, heuristics, or meta-heuristics. Due to the configurable nature of these problems, a given solution approach is generally only developed and tested for a specific variation of one of these classical formulations. However, it is usually possible to adapt a solution technique to fit similar problems.

Exact methods

One of the oldest methods for solving classical scheduling problems involves developing a mixed-integer programming formation for the problem and then solving this formulation using a branch-and-bound algorithm. Patterson (1976) and Stinson et al. (1978) both developed various formulations and branch-and-bound algorithms to solve the resource constrained project scheduling problem. Although they successfully obtained optimal solutions, the solvable problem size was limited.

More recently, constraint programming was developed as an alternative for finding the exact solution of complex optimization problems. Constraint programming seeks to find the optimum solution by eliminating infeasible solutions from an initial set of all possible solutions until only the optimal solution remains. This method was applied by Garrido et al. (2009) and Schutt et al. (2013) to solve the resource constrained project scheduling problem. Both these works found the optimal solutions for small problem instances.

One of the major advantages of both of these exact methods is that highly developed solvers already exist for these methods. A large research effort is continuously being performed by the mathematical optimization community to improve the performance of these solvers. To use these solvers, the problem must only be formulated correctly. However, the complexity of scheduling problems severely limits the effectiveness of exact methods. Most scheduling problems are classified as either NP-hard or NP-complete. When a problem is classified as NP, it is not possible to develop an algorithm that can find the exact solution of all instances of that problem in polynomial time. This means that as the problem size increases, the computational time of any exact algorithm increases exponentially at best.

Heuristics

Heuristics are custom algorithms developed specifically to find a solution for a given problem structure. Unlike exact methods, heuristics do not try to find and prove the optimal solution, but instead only seek to find a good solution. This allows these algorithms to operate much more quickly. Depending on the application, this loss in optimality may be acceptable. For example, when generating the initial production schedules for a new shipbuilding project, a shipyard would likely be satisfied with only obtaining a good solution, as these schedules would regardlessly be altered during the construction of the ship.

Some of the most common heuristics found in literature for scheduling problems are list scheduling heuristics. These algorithms assign a priority to each task, and use these priorities to construct a schedule. List scheduling heuristics ensure that the precedence constraints of a problem are satisfied. Some of these algorithms are rather simple, such as ranking tasks based on their execution time. Cheng and Sin (1990), Hurink and Knust (2001), and Kolisch (1996) compare the performance of various simple list scheduling heuristics for different classical scheduling problems. They find that although these algorithms find solutions extremely quickly, the quality of the solutions is often insufficient. Patterson (1976) finds that the precedence structure strongly affects the solution quality found by simple list scheduling heuristics.

More complicated heuristics have also been proposed and tested on these classical scheduling problems. Luh et al. (1990) and Hoitomt et al. (1990) both developed custom heuristics for parallel machine scheduling that use lagrangian relaxation of the mixed-integer programming formulation. Ulusoy and Özdamar (1994) created a series of optimal short term schedules while only considering the jobs open at a given point in time. These types of methods provide a more robust approach and generate better solutions than simple list scheduling heuristics at the expense of additional computation time.

Meta-heuristics

Meta-heuristics are high level optimization procedures that solve a wide variety of problems. They are often mathematical representations of natural phenomena. Like heuristics, these methods only aim to find a good solution to a problem instead of the optimal one. Unlike heuristics, meta-heuristics are not extensively customized to fit a specific problem. Instead, these procedures interact with the problem as high level black boxes. Common meta-heuristics used in scheduling optimizations are genetic algorithms, simulated annealing, and particle swarm optimization.

Solution representation is very important for the successful implementation of meta-heuristics because it is required to convert the meta-heuristic input/output, typically a vector or series of vectors, into a production schedule. For example, a possible solution could be represented by a vector of the start times of each task. However, such a solution space contains many infeasible solutions when the problem has many precedent constraints. One possible method for avoiding the infeasible region of the solution space is to assign negative penalties in the objective function for infeasibility or to repair infeasible solutions using a custom repair algorithm. Alternatively, a list scheduling approach can also be used, where the meta-heuristic seeks to determine the optimal priorities for the tasks.

Genetic algorithms are a meta-heuristic based on the biological process of evolution. These algorithms are one of the oldest and most commonly used meta-heuristics. In a genetic algorithm, a population of chromosomes is used to represent a group of solutions. New generations of chromosomes are repeatedly produced through selection, crossover, and mutation operators until a stopping condition is met. Over time, the average fitness of the population increases until the population converges on a near optimal solution. Examples of genetic algorithms applied to scheduling problems include Ramachandra and Elmaghraby (2006), Sakalauskas and Felinskas (2006), and Pezzella et al. (2008).

Simulated annealing is a meta-heuristic optimization technique that is loosely based on the annealing operation of metal processing. For simulated annealing, a random solution and starting temperature is initially defined. This temperature is decreased as the algorithm runs. Each step of the algorithm consists of a series of random moves, selected from a neighborhood. Moves that improve the solution are always accepted, and worsening moves are accepted based on an acceptance probability, which decreases with the temperature. Boctor (1996) and Anagnostopoulos and Rabadi (2002) both use simulated annealing to solve theoretical scheduling problems.

Particle swarm optimization is a meta-heuristic that models the movement of a swarm of particles in a solution space, loosely analogous to a flock of birds or swarm of bees. Each particle has some inherent inertia and also moves towards the best solution previously found by the particle itself as well as the best solution found by any particle. The traditional particle swarm optimization is formulated to operate on a continuous solution space, and therefore modifications have been developed to allow the algorithm to work with discrete solution representations, such as priority based list scheduling. Zhang et al. (2005) and Linyi and Yan (2007) solve the resource constrained project scheduling problem using particle swarm optimization.

A strong research effort has also been performed by the meta-heuristic optimization community regarding the development and analysis of hybrid meta-heuristic algorithms. Hybrid algorithms are created by combing two meta-heuristics together. For example, genetic algorithms and simulated annealing can be combined by alternating between the two algorithms, such as Wang et al. (2009); creating custom crossover and mutation operators that are based on simulated annealing, such as Adler (1993); or by other novel techniques, such as Chen and Shahandashti (2009). Meta-heuristics are also combined with other heuristics techniques or algorithms to develop hybrids. For example, Qin and Xu (2007) integrate fuzzy logic with a genetic algorithm and simulated annealing to solve a multi-objective assembly sequence planning problem. Chen and Shahandashti (2009) found that the performance advantages of hybrid algorithms increase as the problem size grows.

Overall, meta-heuristics usually find solutions of better quality for classical scheduling problems than simple heuristics. Meta-heuristics are also more robust since they can also handle a wider variety of problem structures successfully. However, these algorithms usually require additional computational time compared to simple heuristics, as they work with large populations of potential solutions over many generations. It is also difficult for users to understand, tune, and adapt meta-heuristics that operate as high level black boxes.

2.3.2 Automatic Planning in Production Processes

A large body of literature also exists for the automatic scheduling of manufacturing processes, such as automotive and aircraft construction. Processes covered by literature include the production of solar cells (Cheng et al., 2013), semiconductor manufacturing (Mönch et al., 2011), steelmaking continuous casting (Mao et al., 2014), and the CNC end milling process (Kondayya and Krishna, 2012). However, these processes have a much higher focus on mass production techniques than shipbuilding, since a shipyard produces very few products annually compared to other manufacturing facilities. Furthermore, manufacturing processes typically produce large quantities of identical or nearly identical products. This is different from the case of European shipyards building complex ships, which primarily work with one-off constructions.

Although not directly applicable to shipbuilding, production planning optimization projects developed for the manufacturing industry still provide useful insight. For example, Framinan and Ruiz (2010) created a framework for an integrated approach for taking a theoretical planning system and implementing it on a real application. This type of framework is required for implementing an automatic planning method in a real industrial setting. For example, interface and integration issues are not considered by most theoretic planning tools. Safaei et al. (2011) examined machine maintenance issues and incorporated uncertainty in their model, factors also important for shipbuilding.

2.3.3 Automatic Planning in Shipbuilding

The erection, section building, and outfitting processes of shipbuilding can be modeled in terms of classical scheduling problems. For example, the outfitting process involves a set of installation tasks which must be executed by a set of specialized mounting teams, resembling a resource constrained project scheduling problem. However, modeling shipbuilding as a classical scheduling problem is challenging for several reasons. For example, the shipbuilding process contains complex precedence constraints which are not addressed in literature. In outfitting, two adjacent components cannot be installed simultaneously due to safety reasons, but it is irrelevant which component is mounted first. It is also not important in what order a pipe's spools are installed, as long as the mounting team begins with a penetration piece and no component is placed between two already mounted pipes. These sorts of complex conditional precedence constraints cannot be captured directly by classical scheduling problems. Furthermore, the objectives relevant to automatically generating production schedules for shipbuilding, such as resource leveling and ease of construction, are not usually considered in classical formulations.

From a practical standpoint, very few of the required shipbuilding tasks are exactly repeatable. This is worsened by the one-off construction of complex ships, as almost every project is unique. Complex ships also contain a variety of different types of spaces, often densely packed with components. Furthermore, nearly identical tasks in shipbuilding can vary significantly in execution time. This occurs due to local disturbances and the human element required to complete the task. Thermal distortions during welding also cause significant variations between the designed and achieved geometries, adding an additional layer of uncertainty.

However, the existing body of knowledge for theoretical scheduling literature can still be extremely helpful for automatically generating an Erection, Section Building, and Outfitting Plan. The structure of this planning process could be generated by modifying one of these classical problems, or by solving a set of such problems in series, in parallel, or concurrently. Furthermore, literature includes many different solution techniques which are easily modified to fit most representations. The decision of whether to use exact methods, heuristics, or meta-heuristics depends on the requirements for solution quality and computational time.

Literature on the scheduling of real production processes examine some practical issues not present in the classical mathematical scheduling problems. These include issues related to implementation, uncertainty, validation, and data availability. Similar issues must be addressed to successfully generate production schedules for shipbuilding. Furthermore, some of the challenges that arise when implementing automated production techniques in shipbuilding, such as the heterogeneous nature of the product, must also be addressed when attempting to automatically schedule this process.

A detailed literature review of existing research on automatic shipbuilding planning of the erection process is included in Chapter 4. Similarly, Chapter 5 contains a review of section building scheduling literature, and Chapter 7 analyzes existing research on the automatic planning of the outfitting process.

Chapter 3

Integrated Shipbuilding Planning Method*

An Integrated Shipbuilding Planning Method is proposed and developed to answer the research objectives stated in Section 1.3. This chapter describes the major modules that compose this method and how these modules interact with each other. Figure 3.1 provides an overview of the Integrated Shipbuilding Planning Method's structure. This figure shows that the Integrated Shipbuilding Planning Method requires three types of input: the shipyard characteristics, ship geometry, and project milestones. The project milestones are taken as an input instead of a variable since these milestones are defined extremely early in the shipbuilding process. Very little detailed engineering has been completed at this point in time, making it unrealistic to generate production schedules without first completing additional engineering work.

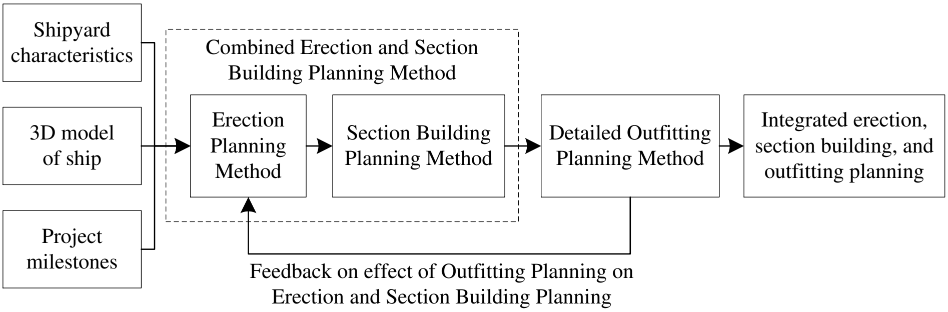


Figure 3.1: Algorithm of the Integrated Shipbuilding Planning Method

The Integrated Shipbuilding Planning Method is composed of three main modules: the Erection Planing Method, the Section Building Planning Method, and the Detailed Outfitting Planning Method. These three modules are executed in series, mimicking the actual planning process of contemporary European shipyards. The order of the modules matches the required information flow. This information flow

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*This chapter is partially based on Rose and Coenen (2014, 2016b).

is described in the next four sections. An additional module, the Combined Erection and Section Building Planning Method, is also included. This module executes the Erection Planning Method and the Section Building Planning Method concurrently. Section 3.4 describes the reasons for creating this module and why the Detailed Outfitting Planning Method is not included.

An iterative feedback loop is created between the three modules. This allows the Integrated Shipbuilding Planning Method to address any conflicts between the modules. For example, the Section Building Planning Method might assign insufficient time for pre-outfitting to a section. The Detailed Outfitting Planning Method might then be unable to successfully schedule all outfitting tasks for that section. This feedback would be given to the Section Building Planning Method, which could then increase the pre-outfitting time of that section.

3.1 Erection Planning Method

The purpose of the Erection Planning Method is to automatically create an optimized Erection Plan. This method is designed to operate at the same level as the shipyard planners creating the Erection Plan. Therefore, this method uses the same inputs and generates the same outputs as these planners. These inputs and outputs are described in Figure 2.5. The Erection Planning Method uses the production milestones, a rudimentary ship geometry, and the erection capabilities of a shipyard to determine the erection time of each section.

Chapter 4 contains a complete description of the Erection Planning Method. This chapter first examines the constraints and objectives that drive the erection process of European shipyards building complex ships. A mathematical model is developed based on the erection process characteristics, and a solution approach is developed for solving the mathematical model. A test case is performed of a pipelaying ship recently built at a Dutch shipyard to demonstrate the feasibility of both the mathematical model and solution approach. The quality of the Erection Plan created by the Erection Planning Method is also compared to the one manually created by the shipyard planners.

3.2 Section Building Planning Method

The Section Building Planning Method automatically generates a Section Building Plan using the same information available to shipyard planners when they create this production schedule. Therefore, Figure 2.6 also describes the inputs and outputs of the Section Building Planning Method. This method combines the erection times of each section with shipyard characteristics and section geometry to determine the assembly and pre-outfitting times of each section. The Section Building Planning Method also determines which sections should be built by subcontractors. A detailed description of this method is presented in Chapter 5. The contents of Chapter 5 mirror those of Chapter 4.

3.3 Detailed Outfitting Planning Method

An Outfitting Plan is automatically generated using the Detailed Outfitting Planning Method. The development and testing of this module of the Integrated Shipbuilding Planning Method is described in Chapter 7. The Detailed Outfitting Planning Method creates an Outfitting Plan on the component level, which is significantly more detailed than the Outfitting Plan currently created by shipyards (as described in Section 2.2). Figure 3.2 shows the inputs and outputs required for the Detailed Outfitting Planning Method. This figure shows that this method uses a ship's geometry, shipyard characteristics, and available time windows for outfitting to determine the outfitting time of each component. The available time windows for outfitting are taken from the Erection and Section Building Plan.

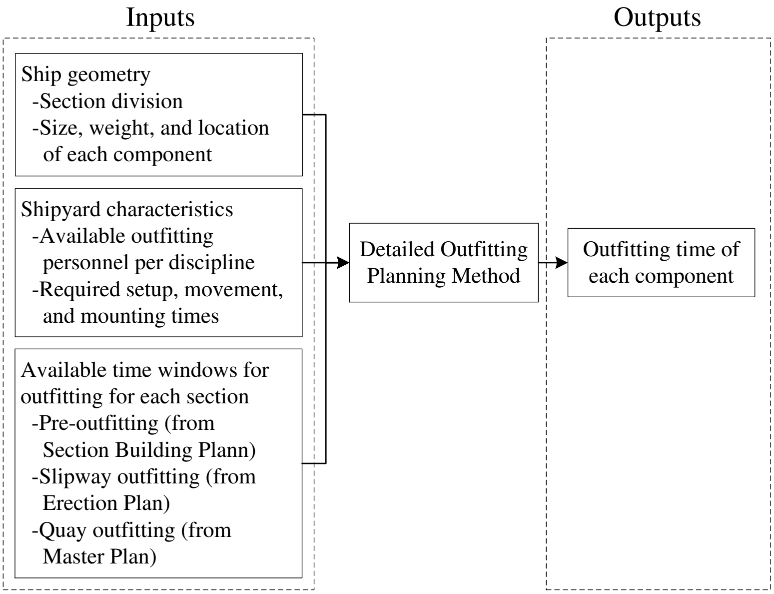

Figure 3.2: Inputs and outputs of the Detailed Outfitting Planning Method

One key difference between the input data required for the Detailed Outfitting Planning Method and the Erection and Section Building Planning Methods is the level of detail required for the ship's geometry. The first two modules only require a ship's general arrangement, section divisions, and rough section characteristics. The Detailed Outfitting Planning Method, however, requires significantly more engineering work to be completed. As a result, fully integrating these methods is not possible, as described in Section 3.4. The requirement to have a detailed ship geometry prior to creating an Outfitting Plan brings up another important issue: production of a ship starts prior to the completion of engineering. This issue and its ramifications are discussed in Section 3.5.

3.4 Combined Erection and Section Building Planning Method

The Erection Planning Method and the Section Building Planning Method are combined together to form the Combined Erection and Section Building Planning Method. This combined method solves both of these modules simultaneously, reducing the sub-optimization resulting from executing the two modules in series. Furthermore, combining these two modules allows the block building process to be incorporated. Building blocks influences both the erection and section building processes as block building requires certain resources from both of these processes.

The Combined Erection and Section Building Planning Method operates on the same level of detail as the Erection Planning Method and the Section Building Planning Method. Figure 3.3 describes the inputs and outputs of the Combined Erection and Section Building Planning Method. This figure shows that the only additional inputs and outputs included relate to the building of blocks.

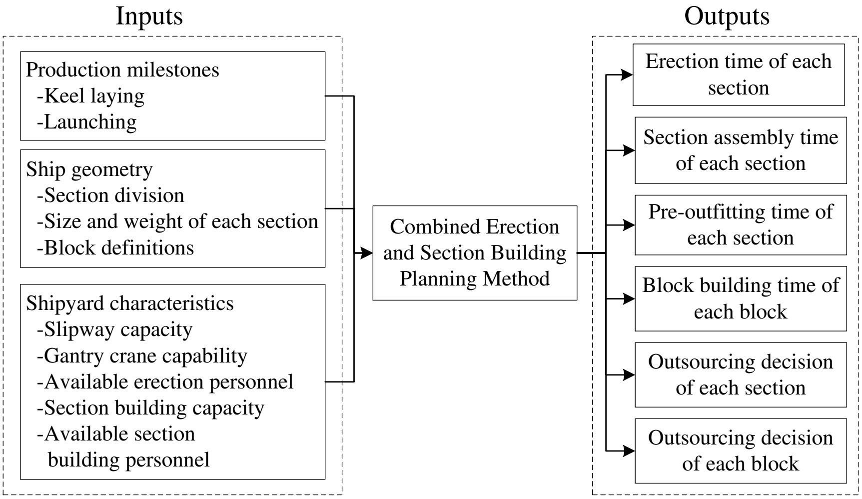

Figure 3.3: Inputs and outputs of the Combined Erection and Section Building Planning Method

The Detailed Outfitting Planning Method, however, is not included in the combined module. This is done for two reasons. First, the problem sizes differ significantly. The Detailed Outfitting Planning Method schedules tens of thousands of outfitting installation tasks, while the other two methods work with roughly one hundred sections. This means that different optimization techniques will be most effective for these methods, making it challenging to combine them. More importantly, these modules require different detail levels of ship geometry definition. The Erection Planning Method and Section Building Planning Method work with a fairly limited ship model available soon after contract signing. The Detailed Outfitting Planning Method, however, cannot operate using such a ship geometry since most outfitting components are not yet defined.

Chapter 6 contains a complete description of the Combined Erection and Section Building Planning Method. This chapter describes the constraints, objectives, mathematical model, and solution technique of this method. A test case applying this combined method is also included in Chapter 6.

3.5 Using Detailed Design Data as Input

This section addresses the issue of using a detailed ship geometry as input when creating an Outfitting Plan, as is done by the Detailed Outfitting Planning Method. Figure 3.4 illustrates this data availability problem. To generate an Outfitting Plan, a sufficiently detailed design of the ship must be available. For such a plan to be effective, however, the plan needs to be generated at the beginning of the production planning phase of the shipbuilding process. This is problematic for the current European shipbuilding process since a sufficiently detailed design of a ship is not yet available at this point in time.

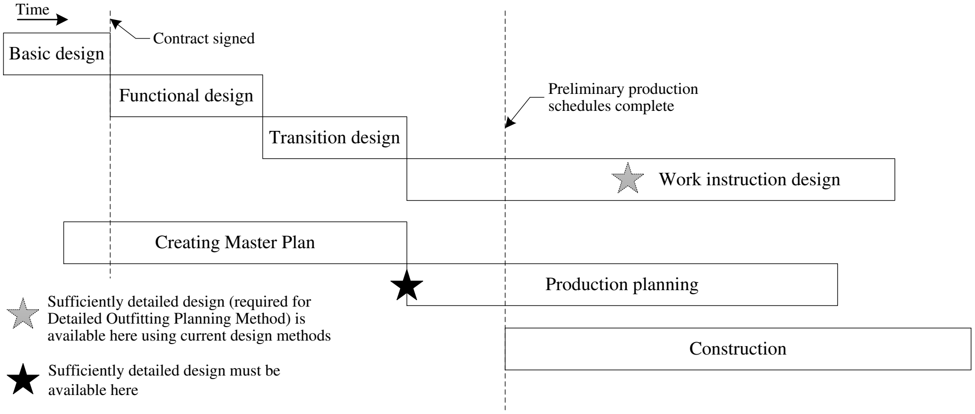

Figure 3.4: Data availability problem of Detailed Outfitting Planning Method

Given the current state of the European shipbuilding industry, several options exist to resolve the dilemma shown in Figure 3.4. First, shipyards could only generate the Outfitting Plan on a simplified, higher level. This is what is currently being done by European shipyards. An Outfitting Plan of this detail is also created by the Erection Planning Method and Section Building Planning Method. However, this approach does not alleviate the outfitting-related problems described in Section 1.1. Secondly, shipyards could delay the start of production until sufficient engineering work has been completed to make a detailed Outfitting Plan. Unfortunately, this type of approach is unrealistic given the one-off nature of complex ships coupled with strong market pressures on fast deliveries.

The third option involves the implementation of automatic design tools. In recent years, research has been conducted by a variety of institutions and companies with the aim of reducing the required time of the ship design process through automating various design tasks. Such tools enable ship designers to consider a wider variety of options in the early design stages and better optimize a ship's design to increase operational efficiency. Computerized methods can offer superior performance compared to traditional iterative design methods, both in terms of speed and quality. Automatic design tools also increase the amount of data available for a ship in the pre-contract design phases.

Automatic design tools have already been developed to perform a variety of ship design functions. The Delft Packing Approach uses a genetic algorithm to generate a series of possible 3D general arrangements for a ship. The general arrangements include the hull shape, bulkheads, decks, tanks, compartment definitions, and location of major systems and equipment (van Oers, 2011). MOSES-CD is currently being developed to automatically generate topology models of large distribution systems during the conceptual design phase. Systems included in the scope of this project are propulsion, electrical power generation, electrical distribution, HVAC, water, and fuel systems (van Es and de Vos, 2012). LBR-5 is a tool developed to optimize sizing and scantlings of ship and offshore structures during the basic design phase. This software is capable of performing multi-objective optimization, creating a Pareto front by altering weights in the objective function (Caprace et al., 2010). The Delft Automatic Pipe Routing Tool uses a discrete particle swarm optimization to concurrently route all of the required piping in a section with the objective of minimizing production costs (Asmara, 2013). Lastly, IMPROVE aims to combine various ship design tools to concurrently consider the ship's structure, production costs, operation costs, performance, and safety (Rigo et al., 2010).

To have a sufficiently detailed design available prior to contract signing it is also necessary to integrate different automatic design tools together. This is an extremely challenging task since the tools were written on different platforms for different purposes. Rigo and Caprace (2011) describe some of the major problems facing efforts to integrate different optimization software:

- Difficulty in sharing data due to lack of standard formats
- Difficulty in transferring data between CAD, CFD, and FEM models
- Variations in required level of detail between different tools
- Most tools are black boxes to users

However, it is possible to overcome these difficulties. For example, IMPROVE successfully combined several different tools. Due to the academic nature of the majority of the efforts to automate the ship design process, the methodology and algorithms used within these tools are also usually published. Moreover, tools exist to aid in the interfacing process of different design tools, such as Quaestor (Grimmelius et al., 2009).

The run times of the automatic routines of the design tools are rather extensive, especially considering the limited amount of time available for early stage design. For example, Asmara (2013) determined that the Delft Automatic Pipe Routing Tool can take upwards of three days to route the piping of a machine room. This limits the application of combining different automatic design tools, especially if the tools are combined in an iterative fashion to provide feedback to each other. Fortunately, the computational power available is currently increasing at an exponential rate. The computational power of personal computers has doubled every 1.5 years for the last few decades (Koomey et al., 2011).

In conclusion, several advanced ship design tools exist, aiming to automate portions of the design process. Each of these tools focuses on a specific portion of the design process, such as pipe routing, general arrangement, or structure design. To have a sufficiently detailed design available at contract signing a significant amount of work must still be performed. Automatic design tools must still be developed for certain tasks, such as insulation and secondary steel design. An integration effort is also required to combine existing tools. However, these challenges should be possible to overcome in the next decade if this research area is given sufficient attention. Having a sufficiently detailed design ready at contract signing would enable shipyards to implement a detailed Outfitting Plan early enough to influence the production process. For this dissertation, the assumption is made that such a sufficiently detailed design is available as input for the Detailed Outfitting Planning Method. This assumption corresponds with the black star shown in Figure 3.4.

Chapter 4

Erection Planning Method*

This chapter develops the Erection Planning Method of the Integrated Shipbuilding Planning Method proposed in Chapter 3. The Erection Planning Method automatically generates an Erection Plan that considers both the steel-related and outfitting-related portions of the erection process. An Erection Plan is a production schedule used by a shipyard to determine at which point in time each of a ship's sections will be erected. A high-quality Erection Plan has two main characteristics. First, such a plan should have level man-hour requirements throughout the entire erection process. Second, the time available for performing the slipway outfitting should be maximized for all compartments densely packed with components. However, an Erection Plan must also satisfy several sets of constraints. These include constraints that ensure a feasible erection sequence and temporal relations between different tasks.

The goal of the developed method is not to find the single, best Erection Plan for a given ship being built at a particular yard. Instead, the method generates a Pareto front of optimal erection schedules which describes the trade-off between the two considered objectives. This range of optimized, feasible schedules is used as a starting point by shipyard planners when developing the Erection Plan for a project. This allows these planners to consider a wider range of possible erection schedules in less time.

To develop the Erection Planning Method, a review was first conducted of the relevant automatic erection scheduling literature. These works were combined with industry observation to develop a qualitative description and mathematical model of the erection process. A solution technique was then developed to solve this mathematical model. The quality and effectiveness of the solution technique was evaluated and validated using a test case of a recently delivered pipelaying ship. An investigation was also conducted into how the Erection Planning Method could be implemented in a modern, European shipyard.

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*This chapter is partially based on Rose and Coenen (2016a,b).

4.1 Literature Review

Although the automatic generation of erection schedules is scarcely covered by literature, the following notable examples exist. Lee et al. (1997) use constraint directed graph search to select the best erection sequence from a predefined set of precedence relationships for a large Korean shipyard. Jinsong et al. (2009) model the erection process as an identical parallel machine-scheduling problem with precedence constraints and machine eligibility restrictions and develop a genetic algorithm to minimize the makespan of their formulation. Hu et al. (2010) expand their work by developing a heuristic based on two planning rules developed for the problem. Bao et al. (2014) further develop this approach using a steerable genetic algorithm method. Meijer et al. (2009) develop a custom heuristic for the erection planning of shipyards building complex ships that considers pre-erection, blocks, resource leveling, large equipment, and closing decks, but provide no details about their method and only provide limited, preliminary results. Caprace et al. (2011) use discrete event simulation to analyze the effect of different block and section splitting strategies of a Brazilian shipyard building a large LNG carrier. Roh and Lee (2007) visually simulate the erection of a very large crude carrier to dynamically provide erection planners with process information while making a plan.

Existing erection planning research excludes or oversimplifies several key aspects necessary for the construction of complex ships. This occurs partially because a majority of these works are designed for Asian shipyards building large quantities of simple ship types. First, the constraints which dictate the feasible erection sequences are rarely described, making it difficult to reproduce or apply their work. When described, these constraints are often taken to be simple start-finish precedence relationships that are defined a priori based on the geometric relationships between the sections. The practical implications of the erection process itself are generally not included, such as the alignment and stability of sections. Furthermore, the effects of outfitting are also excluded, with the exception of Meijer et al. (2009), who indicate that erection schedules should be designed to accommodate the installation time windows of large equipment. However, the outfitting of small and medium-sized components during erection are not addressed. The existing literature also only seeks to optimize a single objective, mainly the makespan of the erection process. However, the erection makespan is not a particularly suitable objective for European shipyards building complex ships.

4.2 Problem Description

The shipbuilding planning process for constructing complex ships in European shipyards begins at contract signing, when the customer and the shipyard agree on the major milestones of the project. These milestones include the start of steel cutting, keel laying, launching, and delivery (Meijer et al., 2009). Meeting these milestones is very important since payments are linked to their completion. Furthermore, shipbuilding contracts often include high penalties for late delivery since customers arrange work for the new ship based on its delivery date (Schank et al., 2005). Delaying the launching of a ship also inherently delays start of the erection of the subsequent ship. Two of the milestones, keel laying and launching, dictate the time window during which the erection process must occur. Keel laying marks when the first section is erected on the slipway, and the ship is moved out of the slipway and moored alongside the quay during launching.

Due to the lack of detailed design data available during contract signing (such as the section divisions of the ship), it is not feasible to create an Erection Plan when the allowable time window for this process is flexible. Early stage planners rely on historical data and experience to set the milestones. Therefore, the goal of erection planners is not to minimize the makespan of the erection process. Instead, the best possible plan should be created within the predetermined time constraints.

Figure 4.1 depicts an Erection Plan for a few sample sections. This figure illustrates that the erection process is composed of three main parts: placing, fixing, and welding. During placing, the large gantry crane above the slipway transports the section to its erection location. This phase ends when the crane is no longer needed. The fixing phase involves tack welding the newly erected section to adjacent sections. Once a section is fixed, it is considered securely attached to the rest of the partially erected ship. The tack welded seams are fully welded during the welding phase. The Erection Plan dictates the start and finish time of the erection process for each section. This plan also inherently dictates the erection sequence of a ship.

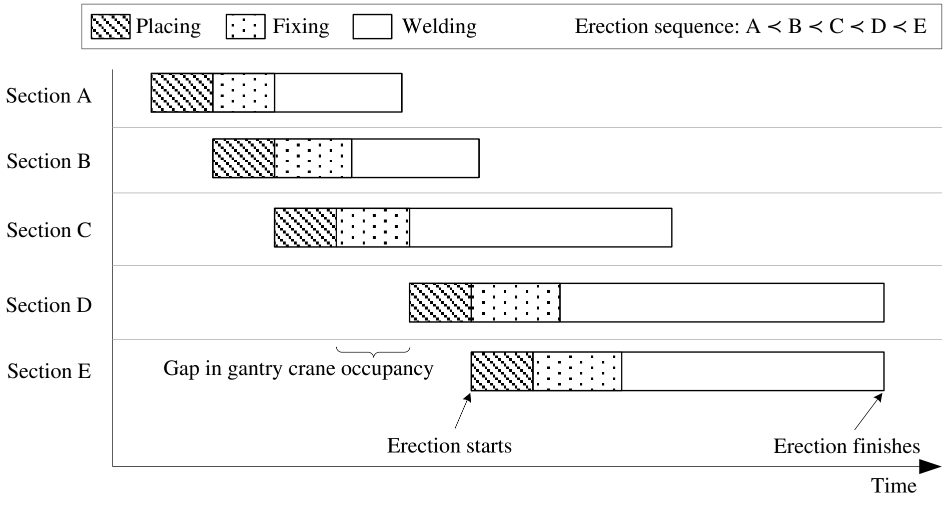
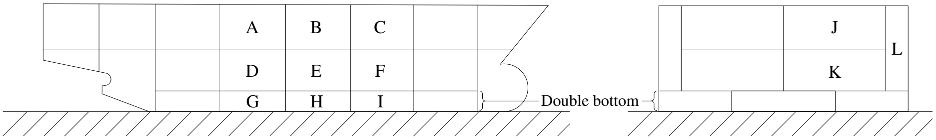


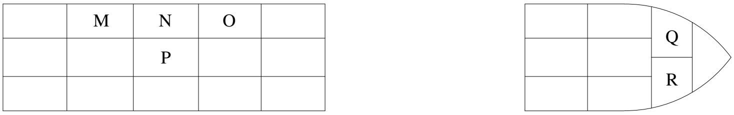
Figure 4.1: Example Erection Plan

4.2.1 Erection Sequence Constraints

Although it is possible to create an almost infinite number of erection schedules for a given shipbuilding project, only a small fraction of those schedules are feasible due to the constraints which restrict the erection process. The first group of these constraints guarantee that a feasible erection sequence is followed. Figure 4.2 presents six different example section arrangements which will be used to illustrate these constraints.



(a) Side view of entire ship (b) Front view of midship sections



(c) Top view of double bottom sections (d) Top view of bow sections

(e) Front view of midship sections (f) Front view of bow sections

Figure 4.2: Example section arrangements to illustrate erection sequence constraints

The first set of erection sequence constraints (Vertical Feasibility Constraints) ensures that when a section is erected all other sections geometrically beneath the newly erected section have already been placed. Some examples of Vertical Feasibility Constraints in Figure 4.2(a) include the following: $D \prec A$, $E \prec B$, and $I \prec F$.

The second set of erection sequence constraints (No Placing Between Constraints) enforces that no section is placed directly between two already erected sections. Ships are constructed in this fashion for alignment reasons and to ensure that the erection crews have sufficient access. These constraints are not simple precedence relationships that can be determined a priori, but instead are a function of the erection sequence itself. For example, consider double bottom section N in Figure 4.2(c). N cannot be installed after M, O, and P are installed. However, many different feasible erection sequences exist that satisfy the No Placing Between Constraints, including: $M \prec N \prec O \prec P$, $P \prec N \prec O \prec M$, $N \prec M \prec O \prec P$, and $O \prec N \prec P \prec M$. In these sample erection sequences, N is sometimes before and sometimes after each of the other sections. The No Placing Between Constraints are also demonstrated in Figure 4.2(a), where B cannot be erected after both A and C are erected. These constraints also inherently enforce that the ship is erected as a single unit. This is important since it prevents the massive amount of additional work that is required to move, align, and connect two partially erected portions of a ship.

The third set of erection sequence constraints (Inside Out Constraints) state that a ship should be built from the center-most sections to the outer-most ones. These constraints exist for access and alignment reasons. However, Inside Out Constraints are not applied to the double bottom sections since access is not an issue for these sections and proper alignment is guaranteed by the No Placing Between Constraints. Figure 4.2(b) depicts the following Inside Out Constraints: $J \prec L$ and $K \prec L$.

In some cases, the No Placing Between Constraints and the Inside Out Constraints conflict with each other. This generally occurs in the oddly shaped regions of the ship, such as the bow, the stern, and around certain cargo holds. When such an infeasible situation occurs, erection planners examine the specific section arrangement to determine which constraint violation will result in the least amount of additional work. This type of constraint relaxation should only be done if absolutely necessary since the additional work due to poor alignment and restricted access can be very high, especially if the sections experience significant deformation (as a result of the heat required for welding) during the section building process.

The fourth set of erection sequence constraints (Sister Section Constraints) indicates when two sections must be erected directly after one another. This type of constraint is required when the alignment of two sections depends on each other. Sister sections usually exist when the section divisions of a ship break from the grid-like pattern and often occur near the bow of the ship. Figure 4.2(d) shows two sister sections, Q and R. Sister Section Constraints cannot be defined using simple precedence relations since it does not matter which of the two sections is erected first. Instead, these constraints only require that the two sections are adjacent to each other in the erection sequence.

The next set of erection sequence constraints (Closing Deck Constraints) specifies that the two side shell sections supporting a closing deck must be erected prior to the closing deck. Without these constraints, the shipyard would need to construct a temporary structure to support the closing deck until the side shell sections are erected, a process which unnecessarily incurs additional cost and risks misalignment. A set of these constraints is shown in Figure 4.2(e), where the following Closing Deck Constraints exist: $S \prec T$ and $U \prec T$.

The sixth set of erection sequence constraints (Structurally Supportive Constraints) states that non-self standing sections must be erected after the sections that provide those sections with support. Like the closing deck constraints, these constraints also exist to prevent the shipyard from having to construct a temporary structure. Two of these constraints are shown in Figure 4.2(f): $W \prec V$ and $W \prec X$.

The last set of erection sequence constraints (Alignment Section Constraints) exists when a specific section is critical to the alignment of the surrounding sections. These constraints require that the critical alignment section is erected before the other sections on its deck. In general, critical alignment sections are located near the center of the ship, both longitudinally and transversely, and are significantly larger than surrounding sections. The moonpool section of a pipelaying ship is an example of a critical alignment section.

Because of the dynamic nature of the No Placing Between Constraints and the Sister Section Constraints, it is not possible to generate a set of precedence relations a priori to describe all feasible erection sequences simultaneously. However, it is possible to determine which sections are feasible to be erected next, given a set of already erected sections. As a result, a set of all feasible erection sequences can be generated. Forward thinking is required to ensure that the No Placing Between Constraints are satisfied. For example, consider the case when A, D, E, and F are already erected in Figure 4.2(a). Although it does not immediately violate any constraints to erect C next, doing so results in a situation where B can never be erected.

4.2.2 Temporal Constraints

Not only does an Erection Plan need to contain a feasible erection sequence, but it must also satisfy a set of time-related constraints. The first set of these constraints (Time Window Constraints) specifies that the erection tasks of all sections must be completed within the allowable time window for erection. This means that all sections must be erected after keel laying and all erection tasks must be completed prior to the launching of the ship. Furthermore, the erection task of each section has a minimum duration because the number of welders that can work simultaneously on a section is limited due to space restrictions. This minimum duration is a function of the section's size.

The next set of these constraints (Large Equipment Constraints) relates to the installation of large equipment, such as the main engines and thrusters. These pieces of equipment often have significant lead times and need to be installed by specialized crews employed by the equipment manufacturer. As a result, the installation time of this equipment is determined when the equipment is purchased, prior to the creation of the Erection Plan. Therefore, the Erection Plan must be developed in such a way to ensure that these pieces of equipment can be installed. This means that the section to which a piece of large equipment is mounted must be in place and prepared prior to that equipment's installation. Furthermore, the sections that prevent the installation of the equipment must be erected after that equipment is installed.

Some pieces of large equipment require that a section is painted prior to their installation while others do not. If painting is required, the welding process of the sections to which that section is mounted must be completed prior to the equipment's installation. However, if painting is not required, the sections to which the large equipment is mounted must only be fixed prior to installing the piece of equipment.

The remainder of the time-related constraints are a function of the erection sequence and dictate the temporal relationships between various erection tasks. The first set of these constraints (Crane Time Constraints) guarantees that the gantry crane above the slipway does not place multiple sections at the same time. These constraints assume that a shipyard only has one gantry crane per slipway, which is typical of European shipyards building complex ship types. The Crane Time Constraints state that before the placing task of a section starts, the placing task of the previously erected section must be completed.

The second set of these constraints (Fixing Time Constraints) ensures that all other sections on which the structural stability of a newly erected section depend have already been securely fixed before that section is placed. Figure 4.2(a) and 4.2(f) depict several example sections which illustrate these constraints. Five different types of fixing relationships can exist between two adjacent sections:

- Horizontal join between two double bottom sections (HB): G-H and H-I
- Non-supportive horizontal join between two non-bottom sections (NHN): A-B, B-C, D-E, and E-F
- Supportive horizontal join between two non-bottom sections (SHN): V-W and W-X
- Vertical join between double bottom and non-bottom section (VBN): D-G, E-H, and F-I
- Vertical join between two non-bottom sections (VNN): A-D, B-E, and C-F

A shipyard issues guidelines on the minimum fixing time required for each of these relationships. Note that the fixing times in Figure 4.1 are actually a simplification since the fixing time can take several different values for a single section if that section is involved in several different types of fixing relationships. For example, a double bottom section might be ready for a second double bottom section to be attached to it after only 1 day, but 2 days might be required before erecting the section immediately above that section.

Fixing Time Constraints are erection sequence dependent since they are only applied to the second section to be erected in the fixing relationship. For example, the initial section to be erected has no Fixing Time Constraints since no other sections exist to which that section can be fixed to at the time of its erection. As a result, a different set of Fixing Time Constraints exist for each feasible erection sequence. The Fixing Time Constraints of some fixing relations are always applied in the same direction due to the following erection sequence constraints: Vertical Feasibility Constraints (VBN and VNN) and Structurally Supportive Constraints (SHN). No Fixing Time Constraints exist between non-adjacent sections.

The last set of these constraints (Outfitting Time Constraints) guarantees that sufficient slipway outfitting time exists for densely packed compartments that also contain large pieces of equipment. It is often more efficient to install the small and medium-sized components in such a space prior to the installation of the large components because the large components significantly restrict access to the compartment. Although the Outfitting Objective seeks to maximize the available outfitting time of all compartments with a significant amount of outfitting work, a minimum available time for outfitting is enforced for these compartments. This is done for two reasons. First, these compartments generally have significantly more components than other compartments as a result of the systems required to service the large equipment. For example, a main engine requires cooling, exhaust, air intake, fuel oil, and lubrication oil systems. Secondly, the Outfitting Time Constraints provide an additional safeguard to ensure that large pieces of equipment are installed on time. The available time for outfitting is defined as the difference between the end of the erection process of the section which composes the floor of a compartment and the beginning of the placing task of the section which composes the ceiling of a compartment.

4.2.3 Objectives

A high-quality Erection Plan should minimize the costs associated with hiring the personnel required to complete the steel-related portion of the erection process. This goal is quantified by the first objective (Resource Objective). The assumption is made that a shipyard should not vary its workforce size during a shipbuilding project due to the costs incurred when changing workforce size. This is especially true for countries with tough labor policies regarding the termination of employees, such as Germany, Spain, Italy, and the Netherlands (Schank et al., 2005). Therefore, the ideal Erection Plan has perfectly level resource requirements. To determine the Resource Objective, a resource utilization curve must be constructed. This curve indicates the number of man-hours required for erection as a function of time. This curve is then compared to the ideal resource requirements, represented by an evenly distributed workload. The difference between these two curves is quantified by summing the square of the difference between the two curves, one of the most commonly used methods for determining resource leveling objectives (Damci and Polat, 2014). The resulting value of this calculation is the Resource Objective.

To construct the resource utilization curve, the individual resource utilization curves of every section are summed. The individual resource utilization curves are assumed to be uniform since the Resource Objective analyses global resource demand instead of examining local fluctuations. Furthermore, the erection planners of the ship used for the test case also use uniform distributions.

To determine the magnitude of the individual resource utilization curves, the total number of erection man-hours required for each section must be known. This value is a function of the erection sequence since welding work required to join two sections together is assigned to the section which was placed second. For example, the very first section that is erected requires no welding work. However, shipyards only predict (and subsequently measure) the erection man-hours for the erection sequence actually used. Since the methodology developed by this chapter seeks to vary the erection sequence, a bi-variable linear regression was used to predict the number of erection man-hours for each section as a function of the erection sequence. The two variables used were section weight and joining circumference. The joining circumference is equal to the circumference of the overlapping area of two sections' bounding boxes. The joining circumference is zero for non-adjacent sections. The quality of the man-hour predictions of the shipyard planners and the bi-variable linear regression were roughly equivalent.

Figure 4.3 compares the quality of the predictions of both the man-hours estimated by the shipyard planners and the bi-variable linear regression. This figure plots the difference between the man-hours required for erection predicted by both methods compared to the actual number of man-hours required when building the ship used for the test case. Note that the parameters of the regression were calculated from the man-hours predicted by the shipyard planners, not from the measured data. Figure 4.3 indicates that both methods had roughly the same accuracy.

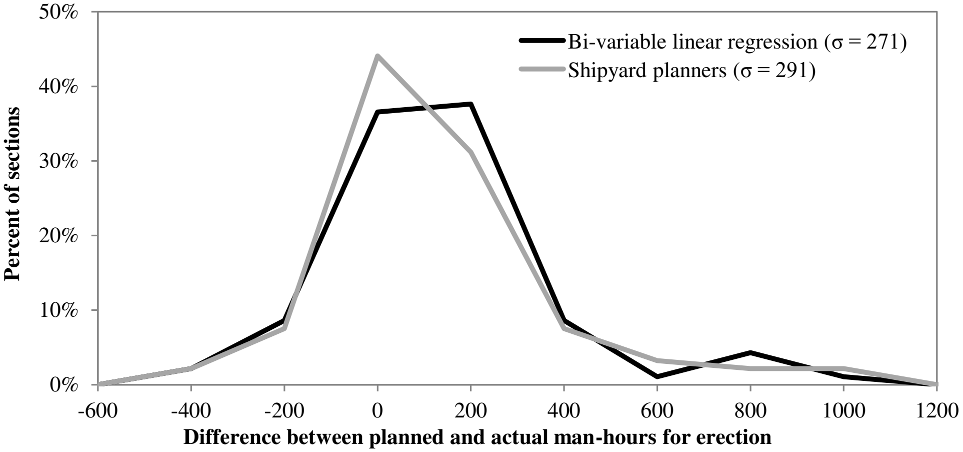


Figure 4.3: Prediction quality of shipyard planners and bi-variable linear regression

A high-quality Erection Plan should also provide sufficient time for slipway outfitting. The second objective (Outfitting Objective) is designed to assess a plan in this respect. Figure 4.4 describes how the Outfitting Objective is constructed for a single compartment. This objective is calculated for each compartment which contains a significant amount of slipway outfitting work. The total Outfitting Objective for an Erection Plan is calculated by performing a weighted sum of the individual compartment objectives based on surface area.

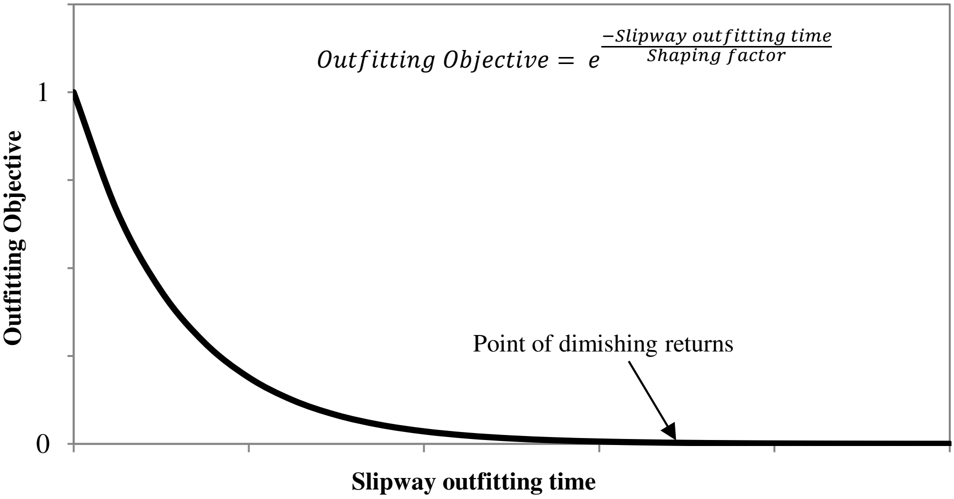


Figure 4.4: Outfitting Objective for a sample compartment

An exponential decay function was selected for the Outfitting Objective since the first few days of slipway outfitting time are the most important. Slipway outfitting time is defined as the difference between the end of the erection process of the sections which compose the floor of a compartment and the beginning of the placing tasks of the sections which compose the ceiling of a compartment. For sections with large equipment, the slipway outfitting time used to calculate the Outfitting Objective is taken to be the slipway outfitting time in excess of the minimum available time for outfitting enforced by the Outfitting Time Constraints. Although additional slipway outfitting time is always beneficial, diminishing returns occur over time. A shaping factor is used to determine the point where additional slipway outfitting days only marginally improve the quality of a plan. The shape of the Outfitting Objective function also rewards an Erection Plan for evenly distributing the slipway outfitting time among the outfitting dense compartments.

4.3 Mathematical Model

The following section contains the mathematical model developed for the erection process of complex ships. This model is based on the process description presented in the previous section. The following notation is used:

i	index used for erection tasks
j	index used for erection tasks
k	index used for compartments
l	index used for large equipment
n	index used for erection sequences
t	index used for time
t_0	start time of erection process
t_f	finish time of erection process
T	set of considered time steps between t_0 and t_f
E	set of erection tasks required to build a ship
x_i	start time of task i (decision variable)
y_i	finish time of task i (decision variable)
w_i	weight of section associated with task i
δ_i	duration required to place section for task i
m_i	number of man-hours required for task i
d_i	minimum duration of task i
$\xi_{i,j}$	joining circumference between sections associated with tasks i and j, 0 if sections are non-adjacent
$f_{i,j}$	duration required for fixing section associated with task i before section associated with task j can be erected, 0 if sections are non-adjacent
Λ_t	set of erection tasks whose sections have already been placed on the slipway at t
Δ_t	set of erection tasks placing sections on the slipway at t
Ω_t	set of erection tasks occurring at t
C	set of outfitting dense compartments of the ship
λ_k	area of compartment k
η_k	slipway outfitting time of compartment k
θ_k	is 1 if there is an Outfitting Time Constraint associated with compartment k, 0 otherwise
γ	minimum slipway outfitting time for densely packed compartments with large equipment
Φ_k	set of tasks required to erect floor of compartment k
Ψ_k	set of tasks required to erect ceiling of compartment k
L	set of large equipment to be installed on the ship
u_l	start time of the installation of large equipment l
v_l	finish time of the installation of large equipment l
ϕ_l	task that erects floor to which large equipment l is mounted
ψ_l	task that erects ceiling above large equipment l
ρ_l	is 1 if section associated with ϕ_l of large equipment l must be painted prior to the installation of l, 0 otherwise
N	set of all feasible erection sequences
P_n	set of start-finish precedence constraints required for erection sequence n
(i, j)	precedence constraint between tasks i and j
q	ideal total resource requirement at any point in time
r_t	achieved total resource requirement at time t

O_{res}	Resource Objective
O_{outf}	Outfitting Objective
β_0	constant parameter of man-hours regression
β_1	weight parameter of man-hours regression
β_2	joining circumference parameter of man-hours regression
α	shaping constant for Outfitting Objective

The man-hours required to erect a section is calculated using Equation 4.1.

$$m_i = \beta_0 + \beta_1 w_i + \beta_2 \sum_{j \in \Lambda_t} \xi_{i,j} \qquad \forall i \in E, t = x_i \tag{4.1}$$

where Λ_t is determined using Equation 4.2

$$\Lambda_t = \{i \in E : x_i + \delta_i \leq t\} \tag{4.2}$$

The ideal total resource requirement at any time is calculated using Equation 4.3. This value corresponds with perfectly level resource requirements.

$$q = \frac{\sum\limits_{i \in E} m_i}{t_f - t_0} \tag{4.3}$$

Equation 4.4 calculates the achieved total resource requirement at each point in time.

$$r_t = \sum_{i \in \Omega_t} \frac{m_i}{y_i - x_i} \qquad \forall t \in T \tag{4.4}$$

where Ω_t is determined using Equation 4.5

$$\Omega_t = \{i \in E : x_i < t \leq y_i\} \tag{4.5}$$

Equation 4.6 calculates the Resource Objective. This objective should be minimized and evaluates to zero for the ideal Erection Plan.

$$O_{res} = \sum_{t \in T} (q - r_t)^2 \tag{4.6}$$

Equation 4.7 determines the slipway outfitting time of each compartment.

$$\eta_k = min(x_i, i \in \Phi_k) - max(y_i, i \in \Psi_k) - \theta_k \gamma \qquad \forall k \in C \tag{4.7}$$

The Outfitting Objective is calculated by Equation 4.8, where the ideal case evaluates to zero and worst case evaluates to one.

$$O_{outf} = \frac{\sum\limits_{k \in C} \left(\lambda_k \ e^{-\eta_k / \alpha} \right)}{\sum\limits_{k \in C} \lambda_k} \tag{4.8}$$

The Time Window Constraints are enforced by Equations 4.9 and 4.10.

$$x_i \geq t_0 \qquad \forall i \in E \tag{4.9}$$

$$y_i \leq t_f \qquad \forall i \in E \tag{4.10}$$

Equation 4.11 ensures that the duration of the erection process of each section exceeds the minimum duration.

$$y_i - x_i \geq d_i \qquad \forall i \in E \tag{4.11}$$

Equation 4.12 guarantees that the Outfitting Time Constraints are satisfied.

$$min(x_i, i \in \Phi_k) - max(y_i, i \in \Psi_k) > \theta_k \gamma \qquad \forall k \in C : \theta_k = 1 \tag{4.12}$$

The Crane Time Constraints are enforced by Equation 4.13.

$$|\Delta_t| \leq 1 \qquad \forall t \in T \tag{4.13}$$

where Δ_t is determined using Equation 4.14

$$\Delta_t = \{i \in E : x_i \leq t \leq x_i + \delta_i\} \tag{4.14}$$

Equation 4.15 ensures that the Fixing Time Constraints are met.

$$x_j + f_{i,j} \leq x_i \qquad \forall i \in E, \forall j \in \Lambda_{x_i} \tag{4.15}$$

The Large Equipment Constraints are guaranteed by Equations 4.16 and 4.17.

$$u_l \geq \begin{cases} y_{\phi_l}, & \text{if } \rho_l = 1 \\ x_{\phi_l}, & \text{if } \rho_l = 0 \end{cases} \qquad \forall l \in L \tag{4.16}$$

$$v_l \leq x_{\psi_l} \qquad \forall l \in L \tag{4.17}$$

Equation 4.18 ensures that a feasible erection sequence is followed. This guarantees that the Vertical Feasibility Constraints, No Placing Between Constraints, Inside Out Constraints, Sister Section Constraints, Closing Deck Constraints, Structurally Supportive Constraints, and Alignment Section Constraints are satisfied.

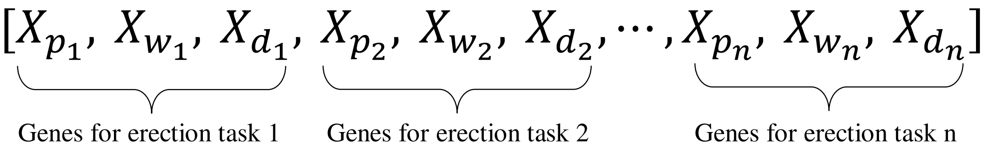
$$x_i < x_j \quad \forall (i,j) \in P_n, \exists n \in N \tag{4.18}$$

4.4 Methodology

Genetic algorithms are a meta-heuristic optimization technique loosely based on the biological process of evolution. This optimization approach was selected because literature has demonstrated that genetic algorithms are capable of effectively solving complex scheduling problems. Specifically, the Non-dominated Sorting Genetic Algorithm II (NSGA-II) was implemented. Deb et al. (2002) contains a complete description of this algorithm. The NSGA-II was selected to automatically generate erection schedules for several key reasons. First, the NSGA-II is designed for multi-objective optimization and therefore seeks to create a Pareto front of solutions instead of finding a single, optimal value. Secondly, this algorithm works with continuous variables instead of the binary or discrete ones commonly found in other genetic algorithms. Both of these characteristics match well with the objective function and input parameters of the proposed mathematical model. Lastly, the NSGA-II has been used to effectively solve a variety of complex optimization problems, including those of the maritime industry. For example, this algorithm has been used to automatically generate general arrangements of complex ships (van Oers and Hopman, 2010), perform aggregate production planning in shipbuilding (Liu et al., 2011), model and optimize a CNC end milling process (Kondayya and Krishna, 2012), schedule joint production and maintenance (Berrichi et al., 2009), solve the generation expansion planning problem (Murugan et al., 2009), examine different cross-training strategies for a flexible assembly cell (Li et al., 2012), and schedule hydro-thermal power plants (Deb and Karthik, 2007).

The performance of a genetic algorithm is heavily dependent on the chromosome definition and fitness function used. A chromosome is the set of values (also called genes) which the algorithm manipulates while searching for an optimal solution. Each chromosome corresponds with a single solution. During each iteration of the genetic algorithm, a new generation of chromosomes is created through selection, crossover, and mutation operators. The fitness function converts each of the newly created chromosomes into a solution (in this case an Erection Plan) and evaluates that solution's strength. The strength of a solution is defined by the objective functions of the mathematical model.

Figure 4.5 describes the chromosome representation used. Because the NSGA-II works with real numbers, each gene is defined to take any value between zero and one. This figure indicates that three genes are associated with each erection task $i \in E$: X_{p_i}, X_{w_i}, and X_{d_i}. The first gene, X_{p_i}, indicates the relative outfitting priority of an erection task. In general, erection tasks with higher priorities are scheduled earlier in the Erection Plan. However, the fitness function does not blindly schedule erection tasks sequentially based on their priority gene, but instead also guarantees that a feasible erection sequence is followed. X_{w_i} represents the amount of waiting time that should be placed in the Erection Plan prior to an erection task. X_{d_i} is a factor that dictates the total duration of the erection process of an erection task.



$$[\underbrace{X_{p_1}, X_{w_1}, X_{d_1}}_{\text{Genes for erection task 1}}, \underbrace{X_{p_2}, X_{w_2}, X_{d_2}}_{\text{Genes for erection task 2}}, \cdots, \underbrace{X_{p_n}, X_{w_n}, X_{d_n}}_{\text{Genes for erection task n}}]$$

Figure 4.5: Chromosome representation

The fitness function converts each chromosome into an Erection Plan. Because the performance of genetic algorithms tends to degrade if the solution space is dominated with infeasible solutions, the fitness function was designed to inherently satisfy a majority of the constraints. However, due to the conflicting nature of several of the constraints, it was not possible to define a fitness function which always produces feasible erection schedules in a reasonable computational time. Fortunately, the NSGA-II is capable of producing satisfactory results when some constraint violation is incorporated in the problem structure (Deb et al., 2002). The fitness function is described in Figure 4.6. The following additional notation is used:

B	set of tasks which have been scheduled
A	set of tasks which can be erected
s	task selected to be erected next
EST_i	earliest start time of task i
h_i	wait time of task i
h_{max}	maximum wait time of a task
d_{max}	maximum duration of a task
X_{p_i}	gene for priority of task i
X_{w_i}	gene for wait time of task i
X_{d_i}	gene for duration of task i
V_{time}	violation of Equation 4.10
V_{equip}	violation of Equation 4.16
M	arbitrarily large number

The first step initializes the fitness function by defining an empty set of erection tasks, B. Each time a task is scheduled in the Erection Plan, this task is added to B. The next step (step 2) creates a set of all tasks which can be erected, A. To be a member of A, a task must satisfy two conditions. First, the task must not already be scheduled. Second, at least one feasible erection sequence must exist where the selected task is scheduled before all currently unscheduled tasks. Because this condition is applied during every iteration, a feasible erection sequence will always be created. The third step of the algorithm selects the task which can be scheduled, $s \in A$, which has the highest priority, X_{p_s}.

The next five steps schedule the selected task in the Erection Plan. Step 4 calculates the earliest start time (EST_s) of this task. The earliest start time is dependent on the following: the Crane Time Constraints, the Fixing Time Constraints, the Outfitting Time Constraints, the second part of the Large Equipment Constraints, and the first part of the Time Window Constraints. By defining the earliest start time based on these constraints, the fitness function guarantees that these constraints are satisfied. The next step (step 5) calculates the amount of waiting time (h_s) to be implemented in the Erection Plan prior to scheduling task s. Waiting time is included in the fitness function since it is not always desirable to perform each erection task at its earliest start time. However, due to the tight time constraints generally present during erection, it is usually desirable to have no waiting time. However, some waiting time would almost always be associated with each task if the waiting time was defined to be proportional to X_w. Therefore, a piecewise function is used to calculate the waiting time. h_{max} is an arbitrarily large maximum waiting time. Steps 6 and 7 calculate the start and finish times of a task, where d_{max} is an arbitrarily large maximum erection duration. Step 8 adds the selected task to B. This process is repeated until all erection tasks are scheduled.

Steps 2 through 6 guarantee that the Erection Plan created by the fitness function satisfies all constraints of the mathematical model with the exception of the second part of the Time Window Constraints and first part of the Large Equipment Constraints. Steps 10 and 11 quantify the violation of these two constraints respectively. Step 12 assesses the fitness of the Erection Plan constructed from the chromosome. If all constraints are satisfied, the fitness is equal to the value of both objective functions. These objective functions evaluate to a value between zero and one. Otherwise, the fitness is based on the magnitude of the constraint violation calculated in steps 10

```
Step 1. Set $B = \emptyset$
Step 2. $A = \{i \in E : i \notin B \wedge (j,i) \notin P_n \quad \forall j \notin B, \exists n \in N\}$
Step 3. Select section $s \in A$ with highest priority $X_{p_s}$
Step 4. $EST_s = max \begin{pmatrix} x_i + \delta_i & \forall i \in B \\ x_i + f_{si} & \forall i \in B \\ y_i + \theta_k \gamma & \forall i \in \Phi_k, \forall k \in C \text{ where } s \in \Psi_k \\ v_l & \forall l \in L \text{ where } \psi_l = s \\ t_0 & \end{pmatrix}$
Step 5. $h_s = \begin{cases} 0, & \text{if } X_{w_s} < 0.5 \\ 2(X_{w_s} - 0.5)h_{max}, & \text{if } X_{w_s} \geq 0.5 \end{cases}$
Step 6. $x_s = EST_s + h_s$
Step 7. $y_s = x_s + (d_{max} - d_s)X_{d_s} + d_s$
Step 8. $B = B \cup \{s\}$
Step 9. Repeat teps 2 through 8 until $B = S$
Step 10. $V_{time} = max(y_s - t_f, \forall s \in S)$
Step 11. $V_{equip} = \sum_{l \in L} \left( \begin{cases} y_{\phi_l} - u_l, & \text{if } \rho_l = 1 \text{ and } y_{\phi_l} - u_l > 0 \\ x_{\psi_l} - u_l, & \text{if } \rho_l = 0 \text{ and } y_{\psi_l} - u_l > 0 \\ 0, & \text{otherwise} \end{cases} \right)$
Step 12. If $V_{time} = 0$ and $V_{equip} = 0$
             Calculate $O_{res}$ and $O_{out}$ using Equations 4.6 and 4.8
         else
             $O_{res} = M + V_{time}/(t_f - t_o)$
             $O_{out} = M + V_{equip}/[(t_f - t_o)|L|]$
```

Figure 4.6: Fitness function

and 11. The value of the fitness function based on the constraint violation is defined so that the resulting fitness values are always greater than some arbitrarily large number. Therefore, an Erection Plan that violates either of the two constraints will always have a worse fitness than a feasible plan. Furthermore, since the constraint violation is defined proportionally to the degree of the violation, higher fitness is assigned to schedules that violate the constraints to a lesser extent.

The erection sequence of the Erection Plan produced by the fitness function does not necessarily match the sequence of the erection priorities (X_p) used to generate the plan. This occurs since the section with the highest erection priority is not always in A. Therefore, the chromosomes are repaired after calculating their fitness so that the erection priorities match the resulting erection sequence. This is done to prevent faulty genetic material from being passed to future generations.

The performance of a genetic algorithm is also strongly influenced by the parameters used by the algorithm itself. Because the purpose of this chapter is to show that it is feasible to solve the developed mathematical model using a multi-objective genetic algorithm and not to optimize its performance or solution quality, the NSGA-II parameters proposed by Deb et al. (2002) were used (population size = 100, crossover probability = 0.9, distribution index for crossover = 20, mutation rate = 1/chromosome length, distribution index for mutation = 20, stopping condition = 250 generations). The performance of the NSGA-II can be improved by optimizing these parameters. For example, Sadeghi et al. (2014) use the Taguchi method to tune a NSGA-II developed for supply chain management. Eiben and Smit (2011) survey the existing methods for tuning the parameters of evolutionary algorithms and provide a conceptual framework for accomplishing this task.

4.5 Test Case

The developed methodology was applied to a pipelaying ship recently built by a Dutch shipyard. This was done to assess the feasibility and quality of the developed mathematical model and solution technique. Table 4.1 contains the relevant characteristics of the ship and its erection process. During the actual construction of this ship, four blocks were created out of fourteen accommodation sections. These blocks were treated as sections for the test case since their creation does not take place on the slipway. The highest accommodation section of the ship was excluded from this analysis since it was erected significantly later than the other sections due to the height restrictions of the slipway.

Table 4.1: Test case characteristics

Number of sections ($\|S\|$)	97
Number of outfitting dense compartment ($\|C\|$)	26
Number of large equipment ($\|L\|$)	15
Placing duration (p_i)	0.5 days
Fixing duration, HB (d_{ij})	1 day
Fixing duration, NHN (d_{ij})	0 days
Fixing duration, SHN (d_{ij})	5 days
Fixing duration, VBN (d_{ij})	2 days
Fixing duration, VNN (d_{ij})	5 days
Minimum available time of slipway outfitting (z)	15 days
Minimum erection duration factor	0.5
Maximum erection duration factor	2.0
Maximum waiting time (wt_{max})	5 days
Outfitting Objective shaping constant (α)	3

Table 4.1 contains two factors used to calculate the minimum and maximum duration of the erection process of each section. The shipyard constructing the test case

ship has guidelines for the preferred erection duration of a section based on that section's weight. An analysis of historical erection data of that shipyard showed that the actual erection durations almost always fell within the described limits. The allowable range of erection durations for each section was calculated by multiplying these factors by the preferred erection duration. An experienced erection foreman was consulted to ensure that it was feasible to erect a section within the minimum erection duration.

The shaping factor for the Outfitting Objective was selected so that the point of diminishing returns for additional slipway outfitting time was roughly equal to 15 days. Consultation with outfitting planners confirmed that this amount of time was more than sufficient to complete the required slipway outfitting time. The Outfitting Objective was calculated for the following densely outfitted compartments: engine rooms, winch rooms, thruster rooms, switchboard rooms, stores, galley, engine control rooms, pipe baskets, workshops, and other small technical spaces. The following large equipment was included in the test case: 6 main diesel generator sets, 2 large pipelaying winches, 4 bow thrusters, and 3 stern thrusters. The generator sets and winches required painting prior to installation, but the thrusters did not. The required time windows for the installation of the large equipment was taken to be the actual installation dates of these components.

4.6 Results

The NSGA-II was coded in MATLAB and run on a 64-bit PC with 16 GB RAM and an 8x 3.50 GHz processor. A single generation took roughly two seconds to evaluate, resulting in a total computational time of nine minutes per trial.

Figure 4.7 contains the Pareto fronts of solutions for ten different trials. The Erection Plan used for the construction of the test case ship is also included. Figure 4.7 indicates that all solutions found by the NSGA-II were superior with respect to both objectives. Therefore, the developed solution technique can feasibly produce high-quality solutions for the proposed mathematical model in a reasonable computational time. However, the genetic algorithm also produced somewhat inconsistent results. The best trial produced solutions with objective values which were roughly twice as low as the worst trials. Properly tuning the parameters of the NSGA-II would most likely improve its performance and consistency.

Figure 4.8 shows the best value found for both objectives as a function of the number of generations performed. The Pareto front used in Figure 4.8 is labeled in Figure 4.7. Figure 4.8 indicates that the initial population contained no feasible solutions, since the best values found for both objectives were greater than one. After a few generations, the NSGA-II was able to find at least one solution that met the first part of the Large Equipment Constraints (since the Outfitting Objective took a value of one). An additional twenty generations were required to find a solution that satisfied all constraints. The initial feasible solutions were of worse quality than the one created by the shipyard planners. However, the solution quality found by the NSGA-II steadily improved, surpassing the real plan. A similar behavior was observed for the other trials.

Figures 4.9 and 4.10 compare the quality of one of the best solutions produced by the NSGA-II with the actual Erection Plan of the test case ship. The axes labels

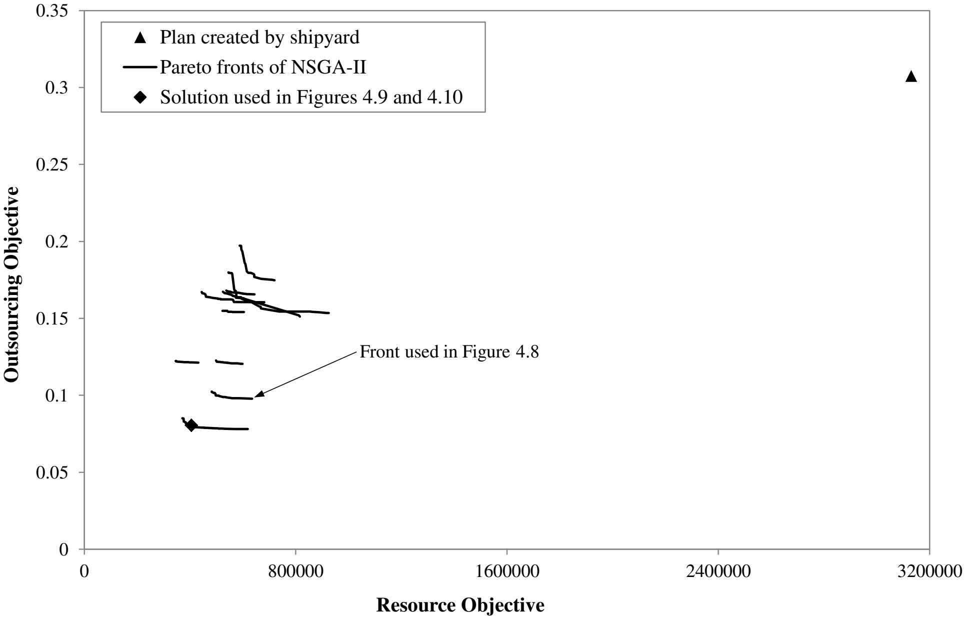


Figure 4.7: Pareto fronts for test case ship

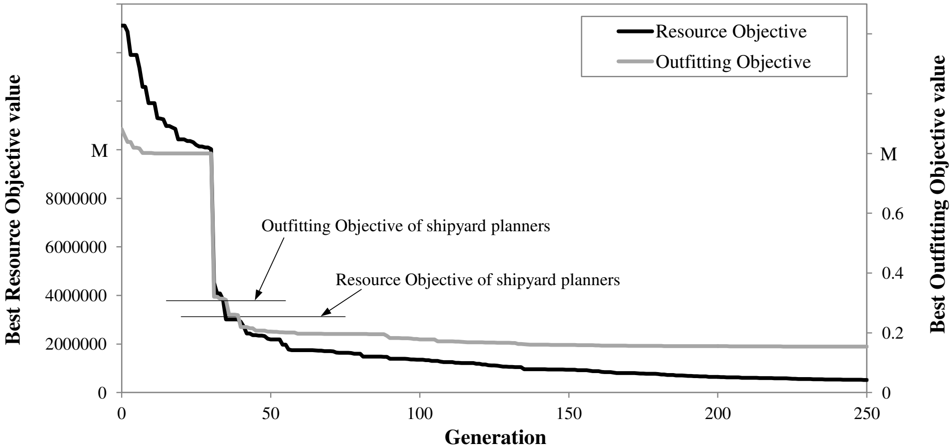


Figure 4.8: Effect of generation number on solution quality

have been removed from this figure at the request of Royal IHC. The Resource and Outsourcing Objective values of the selected solution are indicated in Figure 4.8. This figure indicates that the selected solution is part of the best Pareto front found for the test case. Figure 4.9 describes the number of man-hours required per day. The ideal resource distribution curve is also included. This figure indicates that the Erection Plan created by the shipyard has worse performance with regards to resource leveling. This plan required two significant peaks in resource demand which were not present

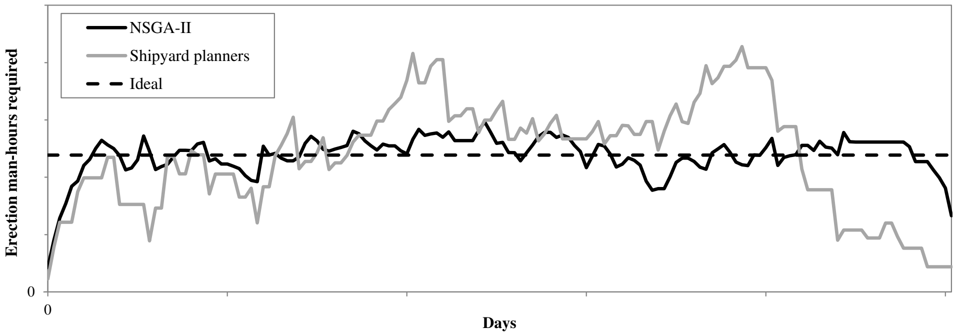


Figure 4.9: Resource curves (basis of Resource Objective)

in the solutions found by the NSGA-II. Figure 4.8 proves that it is possible to use the developed methodology to create an Erection Plan with level resource demands.

Figure 4.10 examines the selected solution with respect to the Outfitting Objective by showing the percent of densely outfitted area grouped by the additional time for slipway outfitting. This figure indicates that the Erection Plan created by the shipyard had the more inconsistent behavior with respect to slipway outfitting. Roughly 50% of the required outfitting area had either no time alloted for slipway outfitting or more than 50 days. The solution generated by the NSGA-II allocated between 10 and 30 days of slipway outfitting time for a majority of outfitting dense compartments. Figure 4.10 suggests that the shape of the function driving the Outfitting Objective achieved the desired effect, evenly spreading the available additional slipway time between the different compartments.

Appendix A visualizes the erection sequences of the selected solution produced

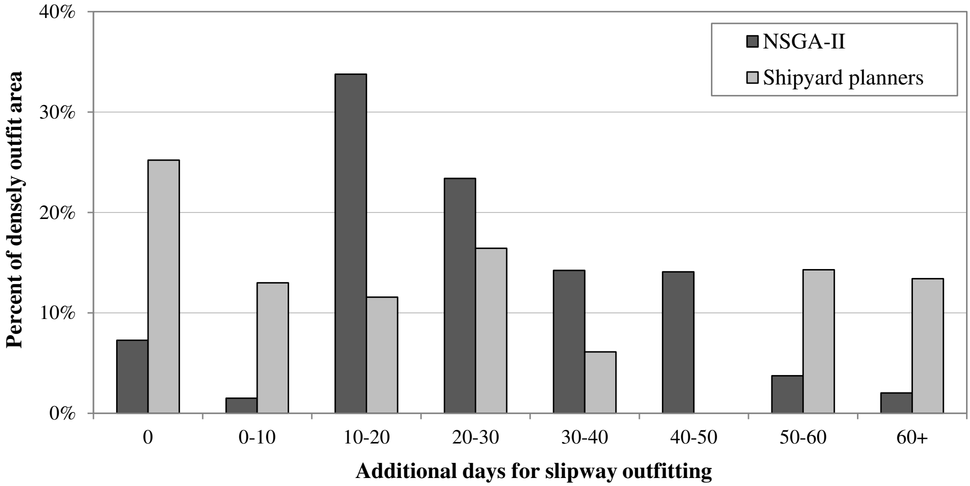


Figure 4.10: Time available for slipway outfitting (basis of Outfitting Objective)

by the NSGA-II and the Erection Plan created by the shipyard planners. In general, these two sequences are very similar. Both sequences start with the same section, the double bottom section of the moonpool. This section is the most central section of the ship. From these, both sequences erect the double bottom in both directions, initially focusing on the main engine room (located at the bow of the ship). This allowed for the main engines to be installed on time. On the second level, both schedules again began with the moonpool section, using this section as a starting point to build in both directions. The accommodation sections were erected near the end of both erection sequences.

However, several differences exist between the two erection sequences. First, the one created by the shipyard planners is very symmetrical. In almost all cases, matching port and starboard sections were erected right after one another. Conversely, the sequence produced by the NSGA-II erected sections in a somewhat asymmetrical manner. This occurred since no constraints or objectives of the Erection Planning Method pertained to symmetry. Second, the sequence created by the NSGA-II kept the main engine room open as long as possible, delaying the erection of the accommodation sections as long as possible. The shipyard planners chose to close the engine rooms prior to closing the baskets (located aft of the moonpool section). Lastly, the sequence created by the NGSA-II built towards the stern of the ship much faster. This resulted in two sections being erected along the centerline of the ship without the corresponding port and starboard sections. The shipyard planners, however, erected sections toward the stern of the ship in a slower, more even manner.

4.7 Validation

The Validation Square was used to validate the Erection Planning Method. The Validation Square is a framework proposed by Seepersad et al. (2005) for validating design methods. The planning problem examined in this chapter is not purely a scheduling optimization, but instead has many elements of a design problem. The main goal of the Erection Planning Method is to design the best initial plan possible given the limited information available prior to the start of production. Designing such a schedule is a subjective process, as some of the constraints and objectives that govern the erection process are flexible. Ultimately, the objectively optimal schedule will change over time, as real life disturbances alter the input data used to generate the Erection Plan. The Validation Square, described in Figure 4.11, validates a design method by demonstrating the method's usefulness at performing its purpose. This is done by examining the design method relative to the four regions of the Validation Square: theoretical structural validity, empirical structural validity, empirical performance validity, and theoretical performance validity.

To determine a method's theoretical structural validity, the individual constructs composing the method should first be validated. Seepersad et al. (2005) suggest examining relevant literature to validate these constructs. Sections 4.1 and 2.3.1 describe the literature reviewed to evaluate the underlying fundamentals of the erection process and scheduling problems, respectively. However, none of the examined literature adequately describes the erection process of European shipyards building complex ships. Therefore, a series of validation sessions were conducted with experienced shipbuilding personnel to validate the constraints and objectives used by

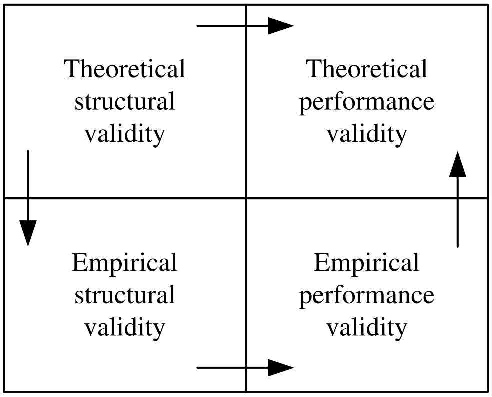


Figure 4.11: The Validation Square, adapted from Seepersad et al. (2005)

the Erection Planning Method. Appendix B contains a description of these sessions' participants. All objectives and constraints were individually presented during these sessions. The following feedback was provided by the participants:

- The Time Window Constraints should be expanded to consider the flexibility of the end point of erection. This is important for ships with propeller shafts since the shaft alignment process must be completed prior to launching but cannot commence until all sections above the shafting have been erected.
- Although the Fixing Time Constraints are valid, the required time for vertical fixing time used was too short. When asked to specify the required time, no concrete answer was given. The general opinion was this time should be between 10-15 days, but it can be done faster if required.
- The additional time required for slipway outfitting for densely packed areas is no more than five days.
- Additional constraints could be included for the case when a partially-erected ship must be moved down the slipway. This occurs when two ships are built in tandem.
- The ideal resource demand curve may not be flat depending on the characteristics of a ship, other projects, and holidays.
- The interaction between the blasting and painting of ballast tanks and erection are not included.
- The height of a ship during erection can potentially limit crane movements. An additional constraint should be added to account for this.
- Double bottom sections adjacent in the transverse direction should be erected as a group (starting with the center section) for alignment reasons.
- The number of sections being erected at any point in time should be limited to ensure the foreman can give adequate attention to every section.

The second step of determining a method's theoretical structural validity is to accept the consistency of the method. This is done by demonstrating that adequate input data is available for all parts of the method. The validation sessions described in the previous paragraph were also used to assess the availability of the required input data. During these sessions, the participants were shown the required inputs of the Erection Planning Method and asked if this information was available at the beginning of the erection planning process. The participants agreed that all required input data is available in some form, but section weights and erection man-hours are initially based on crude estimation techniques. As more of a ship's engineering work is completed, these two values are refined.

A method's empirical structural validity is demonstrated by showing that the example problems used to assess the method are similar enough to the actual problems for which the method was designed. The Erection Planning Method was evaluated using a test case of a pipelaying ship recently built by a Dutch shipyard (described in Section 4.5). Only information available during the planning phase of the shipbuilding process was used when performing this test case. For example, the erection man-hour estimations available to the shipyard planners were used instead of the actual man-hours recorded during the ship's construction.

To determine a method's empirical performance validity, the method should be tested on some example problems. For the Erection Planning Method, the pipelaying ship mentioned in the previous paragraph was used. First, metrics that measure the usefulness of the method must be defined. For the Erection Planning Method, these metrics are the objectives of the mathematical model, the Resource and Slipway Outfitting Objectives. Second, the example problem should be used to show the usefulness of applying the method. This was done by comparing the Erection Plan created using the Erection Planning Method with the one created manually by the shipyard planners (see Section 4.6). It was shown that the Erection Planning Method was capable of producing superior production schedules relative to the examined metrics.

Seepersad et al. (2005) argue that the theoretical performance validity of a method is induced from the other three elements of the Validation Square. This implies that the method is useful beyond the examined example problems. To reinforce this concept, the participants of the validation sessions were asked if they thought the Erection Planning Method could be generally applied to new shipbuilding projects. The resulting opinion was that it was possible, but it might be necessary to add some additional constraints specifically tailored to the project.

This section described how the Validation Square framework was used to validate the Erection Planning Method. Although the Erection Planning Method satisfied the main constructs of the Validation Square, some constraints which potentially drive the erection process were not included. The additional constraints suggested during the validation sessions could be easily implemented due to the flexible nature of algorithms used by the Erection Planning Method to generate production schedules. However, some of these constraints are subjective in nature, and the participants proposing the constraints also admitted that it is often possible to violate them. Ultimately, the discretion of the shipyard implementing the Erection Planning Method should be used to determine which objective and constraints are most suitable for their own production process and the ships they are building.

4.8 Implementation

The methodology developed in this chapter is not designed to replace existing section building planners, but instead enhance their decision making abilities. The developed methodology is useful as a tool for automatically creating a set of initial production schedules. The judgment of the planners would still be required to select one of several promising schedules as the starting point of the Erection Plan. Furthermore, planners would still adjust the schedule to fit the specific constraints of the project. For example, some section types might be particularly difficult to align and fix, and therefore the shipyard may want to prioritize erecting these sections early and assign additional time to these sections. Delays in the previous project or additional work from side projects might also require that adjustments be made to the Section Building Plan.

However, only generating an initial optimized Erection Plan does not guarantee a smooth execution of the process throughout its entire duration. To accomplish this, the Erection Planning Method should be integrated into the production process. Phanden et al. (2011) present a literature review of three common approaches for integrating automatic scheduling tools in production processes: the non-linear approach, closed loop approach, and distributed approach. Because the erection process is relatively slow compared to the time required to generate updated schedules, it would be feasible to use the closed loop approach for this application. This approach dynamically generates production schedules based on the current state of the process. Shipyard planners already release weekly updates to account for any delays or last minute changes. Therefore, it is possible to re-optimize the Erection Plan each week to account for these disturbances. Ultimately, the aim is to create a fully integrated system for managing the erection process, such as the system designed by Mourtzis (2005) for ship repair operations.

4.9 Conclusion

This chapter describes the Erection Planning Method module of the Integrated Shipbuilding Planning Method. To develop this module, a mathematical model was created for the erection process of European shipyards building complex ships. This model includes the effects of slipway outfitting by seeking to maximize the available time for the installation of minor outfitting components on the slipway and by guaranteeing that the Erection Plan is compatible with the installation time windows of large equipment.

A solution technique, based on the NSGA-II, was also developed for solving the proposed mathematical model. A test case of a pipelaying ship was performed to demonstrate the feasibility of both the mathematical model and the solution technique. This test case proved that it was possible to generate a set of feasible erection schedules in a reasonable computational time. The schedules produced by the developed methodology were superior to the one manually created by the shipyard planner. The method was also validated using the Validation Square framework.

Due to the complex and dynamic nature of the erection planning process, the developed methodology is not meant to replace existing shipyard planners. Instead, the Pareto front of optimized erection schedules could be provided to these planners at the start of a shipbuilding project. The planners could then use this information combined with their own experience to draft the initial Erection Plan. This type of approach allows the planners to see the trade-off between resource leveling and slipway outfitting. Furthermore, the planners would be able to produce a higher quality plan in less time that is more likely to satisfy all the constraints dictating the erection process. The developed methodology is used to create the erection times of each section required as input for the Section Building Planning Method. This method is described in detail in the following chapter.

Chapter 5

Section Building Planning Method*

The Section Building Planning Method is developed in this chapter. This module of the Integrated Shipbuilding Planning Method automatically generates a Section Building Plan for a complex ship. The Erection Plan is used as a basis for planning the section assembly process. This process involves welding together steel plates and profiles to create a ship's sections. The production plans of the assembly process are referred to as the Section Building Plan. The Section Building Plan must be designed in such a way that each section is ready to be erected at the time required by the Erection Plan. The Section Building Plan indicates when each section is assembled as well as which sections are built on-site and which sections are outsourced. This plan also sets the time period for which the section is available for pre-outfitting.

The Section Building Plan is often created with vastly insufficient consideration for outfitting. It is not uncommon for shipyards to assign a fixed time period (e.g. two weeks) to each section for pre-outfitting regardless of the section's type, size, and required outfitting work. This leads to uneven outfitting workloads, which in turn often results in crowded working conditions, a failure to pre-outfit as many components as possible, disorganization, and rework. Automatic detailed outfitting planning methods, such as the works of Wei (2012), König et al. (2007), and Rose and Coenen (2015b), also require a Section Building Plan that adequately considers the required time for pre-outfitting.

A high-quality Section Building Plan has two main characteristics. First, this plan should have a relatively even workload for both the section assembly process and outfitting. Having an even workload is important because it is costly for European shipyards and subcontractors to constantly vary their workforce size in the short term. Secondly, the number of outsourced sections should be minimized since performing the required steelwork is strategically important to the shipyard.

Due to the sometimes conflicting nature of the objectives which dictate a high-quality section building schedule, the method does not generate a single solution. Instead, a Pareto front of optimal schedules is created, evaluating schedules on the

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*This chapter is partially based on Rose and Coenen (2016b).

evenness of the required workload and the number of sections outsourced. The results of this method can be used to enhance the decision-making abilities of existing shipyard planners.

This chapter first presents a review of existing section building planning literature. Next, a qualitative description and mathematical model of the section building process are provided. The algorithms behind the Section Building Planning Method are then described, and a test case is presented to verify and validate this method. The chapter concludes with a brief discussion about the implementation of the method.

5.1 Literature Review

When considering the planning of the section assembly process, past research has mainly focused on the spatial scheduling of section assembly halls. Zheng et al. (2011) develop a greedy heuristic algorithm to minimize the makespan of the spatial scheduling of the section assembly process and show their algorithm outperforms grid algorithms and manual methods. Zheng et al. (2012) also develop a heuristic to address the same problem and show that their method finds better solutions than CPLEX and a genetic algorithm when solving large-scale problems. Zhuo et al. (2012) model section assembly planning as two sequential decisions: rule-based dispatching and static spatial configuration. These authors develop a hybrid planning method that uses discrete-event simulation to perform look-ahead scheduling. Koh et al. (2011) develop a 2D packing model for the spacial scheduling of a mega-black assembly yard, and solve this model using a genetic algorithm based heuristic. Although these approaches are well suited for Asian shipyards producing high volumes of large, steel intensive cargo ships, they do not adequately model the section assembly process of European shipyards building complex ships. Even though space constraints are still a consideration for these shipyards, issues such as ensuring the required outfitting tasks can be completed and maintaining an evenly distributed workload must also be considered.

Other works have focused on locally planning specific portions of the section assembly process. Seo et al. (2007) model section assembly planning as a constraint satisfaction problem considering the precedence relations between the assembly operations. These authors use case-based reasoning to creating detailed assembly schedules for single sections. Cho et al. (1996) develop an automatic process planning system for the assembly of a single section, where a network-type representation is used to describe each section. Case-based and rule-based reasoning are used for the planning of the assembly process, cutting, and welding operations. Cho et al. (1999) develop a system for automatically determining the welding postures, methods, equipment, and materials required for building a section based on a section's geometry and assembly sequence. These types of research are not directly applicable to the global planning of the section assembly process since the sections are considered individually.

Kim et al. (2002) use a constraint based approach to create a Section Building Plan that considers both the number of sections that must be outsourced and the required workload distribution. An algorithm based on the Constraints Satisfaction Problem technique is proposed to solve their mathematical model. Although the formulation presented in this paper resembles the section assembly process of European shipyards building complex ships, the effects of outfitting are excluded.

Some of the gaps of past research focusing on the section assembly process is addressed by literature from the operations research community, which has excelled at modeling and solving complex planning problems. For example, Pratap et al. (2015a) create a mixed-integer programming model of the operations of a bulk material port terminal which simultaneously considers the internal operations of the port and the berthing order of the ships. These authors develop both a genetic algorithm coupled with a greedy heuristic and a block-based evolutionary algorithm to solve their formulation. Ziarnetzky and Mönch (2016) propose three different formulations for the production planning of semiconductor wafers, seeking to optimize the use of expensive equipment required for both production and engineering related tasks. A simulation model was used to compare the performance of these formulations.

Not only does operations research literature provide guidance on how to model complex planning problems, but it also provides insight into solving multi-objective optimization problems. None of the previous research of the section assembly process constructed Pareto fronts of non-dominated solutions. For example, Berrichi et al. (2009) examine the joint production and maintenance scheduling problem by finding the best assignment for jobs on machines to minimize the makespan and system unavailability. These authors compare the performance of two genetic algorithms, the Weighted Sum Genetic Algorithm and Non-dominated Sorting Genetic Algorithm (NSGA-II). Pratap et al. (2015b) develop a modified version of the NSGA-II to schedule ships berthing in bulk material handing ports, seeking to minimize ship waiting times and deviation from customer priority.

5.2 Problem Description

For this research, the assumption is made that a shipyard seeks to maximize its capacity in terms of the number of ships delivered. As a result, the Erection Plan of the ship is leading and will be used as input for creating the Section Building Plan. The Erection Plan indicates the time each section is placed on the slipway. Figure 5.1 shows an example Section Building Plan for five sections. This figure indicates that the sections undergo the erection process in a sequential, non-overlapping manner. The Section Building Plan is designed in a way to ensure that the section assembly process does not hinder erection. Each of the sections that are built on site (A, B, and E) have an assembly task and a pre-outfitting task. The plates and profiles composing the section are welded together during the assembly task. Outfitting components are installed in the section during the pre-outfitting task. These two tasks overlap slightly. This is done because it is easier to install some outfitting components (such as large pipes inside double bottom sections) prior to the completion of assembly. It is also possible to perform some outfitting work simultaneously with assembly during the later stages of assembly. At the conclusion of the pre-outfitting task, a buffer is included prior to erection. During this time, the section is transported, painted, and stored. These tasks are not modeled individually in this chapter since that expands the scope beyond the section assembly process. For example, the resources required to transport sections for the assembly process are also used for the erection process. Some additional time is included in this buffer to account for any delays that are incurred during assembly, pre-outfitting, and painting. No time frames for assembly and pre-outfitting are defined for the sections that are outsourced (C and D). Instead, the assumption is made that the company building the section will have adequate safeguards built into their own plan to deliver the section on time.

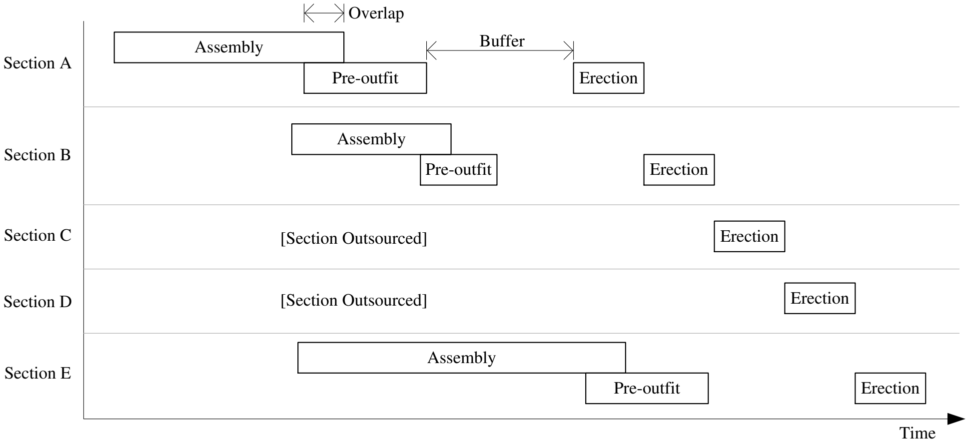


Figure 5.1: Example Section Building Plan

Although it is possible to vary the durations of the overlap between the assembly task and the pre-outfitting task, this time has usually been defined by a shipyard using years of experience. Therefore, a shipyard is free to alter the duration of pre-outfitting tasks, duration of assembly tasks, duration of buffers, and which sections to outsource.

Several constraints restrict the possible section building schedules that can be implemented in a shipyard. First, the pre-outfitting and assembly tasks have minimum durations (Task Duration Constraints). The minimum duration of the assembly process of a section is dictated by the total required man-hours required to assemble the section and the number of workers that can safely work simultaneously on that section. The minimum length of the pre-outfitting task is set in such a way to ensure that the subcontractors performing the outfitting work have an adequate opportunity to incorporate the required pre-outfitting work into their own schedules. A minimum buffer length also exists to ensure that the section building process does not hinder the erection process. Shipyards generally use their experience to set these minimum durations. Although not technically required, shipyards generally also set maximum durations of the buffer due to storage space restrictions and the associated storage costs.

The section assembly process is also limited by the available space in the section building hall (Floor Space Constraint). As mentioned in the literature review, European shipyard planners do not typically address this constraint by solving a dynamic 2D space allocation bin packing problem. Instead, they merely ensure that the number of sections being built at any given point in time does not exceed some pre-determined limit for a given facility.

This approach works for the construction of complex ships since the section building process is less focused on steelwork and more on outfitting, which means that the sections are generally not packed together in the densest possible arrangement in the section building hall. Instead, the concept of a section bed is often used. A section bed is an area of the section building hall used to assemble and pre-outfit a section. It is also possible for two smaller sections, in terms of required floor area, to occupy the same section bed simultaneously. Although the number of section beds available in a given section building hall is constant over time, the number of section beds available to a given shipbuilding project takes a trapezoidal shape. This occurs since the section building process can take a significant amount of time (upwards of eight weeks for some sections) and sections are only required by the erection process one at a time. Therefore, the usage of section beds must be gradually transferred from one shipbuilding project to the next. Figure 5.2 illustrates an example of the Floor Space Constraint for the section building process. Section beds do not necessarily need to be physical locations in the section building hall. They are also defined as the number of sections a shipyard is capable of assembling at a given time. In this work, such a definition of a section bed is used. This is done to match the planning rules of the shipyard used for the test case so that the results may be directly compared.

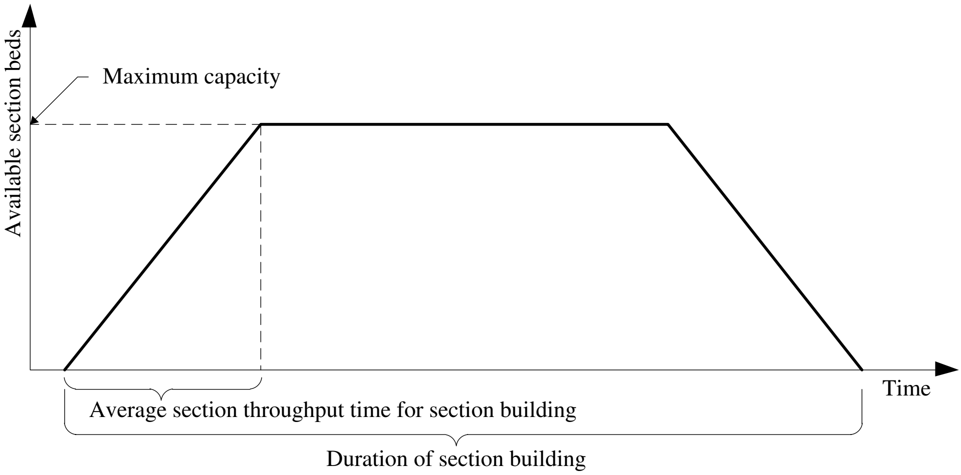


Figure 5.2: Example Floor Space Constraint

The quality of a Section Building Plan depends on two main factors. First, the plan should prevent fluctuations in the required resource levels for all section assembly and outfitting disciplines (Resource Objective). Similar to the Floor Space Constraint, the ideal resource demand curve for a given discipline takes the shape of a trapezoid. This ensures a smooth transition between different shipbuilding projects. Because of the differences in the durations and required workload of involved disciplines, separate ideal resource demand curves are constructed for each discipline. Figure 5.3 describes how the ideal resource demand curve is created for a sample discipline. A curve describing the actual resource requirements of a given section building schedule is compared with the ideal resource demand curve to assess the quality of the Section Building Plan in terms of resource leveling. The disparity between the achieved and ideal resource demands is quantified by summing the square of the difference between the two curves. This method was selected because it is one of the most common methods for assessing a resource leveling objective (Damci and Polat, 2014). The total quality of a given Section Building Plan in terms of resource leveling is calculated by summing the individual Resource Objectives for each of the considered disciplines. It is necessary to create separate resource demand curves for section building and each of the outfitting disciplines since different skill sets are required for each of these tasks. Furthermore, different subcontractors are usually responsible for the different disciplines.

To construct the achieved resource distribution curves, the distribution of resources required during a given task must first be determined. For assembly, shipyard planners generally construct these distributions manually for each section based on the experience of steelwork planners. Figure 5.4 compares the accuracy of these distributions to a uniform distribution for 54 complex ship sections. The sections used were those of the test case ship described in Section 5.5 that were built on-site. Figure 5.4 contains the distribution of the difference between planned and actual weekly man-hours for each of the sections. Only the weeks during which hours were planned or recorded were included. This figure indicates that using a uniform distribution to model the resource distribution for the assembly task of a given section was roughly as accurate as the estimations made by the shipyard planners. Therefore, uniform distributions were selected to model assembly tasks. This decision was reinforced by the fact that the goal of this research is to examine resource usage on a global scale. Uniform distributions were also selected to model outfitting tasks.

The second quality on which a Section Building Plan can be assessed is the percentage of required work that is performed at the shipyard (Outsourcing Objective). An ideal plan should aim to outsource as few sections as possible. Performing assembly and pre-outfitting work on-site is in the strategic interest of a shipyard since each time a section is outsourced the supplier building the section takes a portion of the profit. Furthermore, the shipyard has more control over the assembly and pre-outfitting process if it is performed at the shipyard itself.

Although these two objectives do not absolutely conflict with each other, a trade

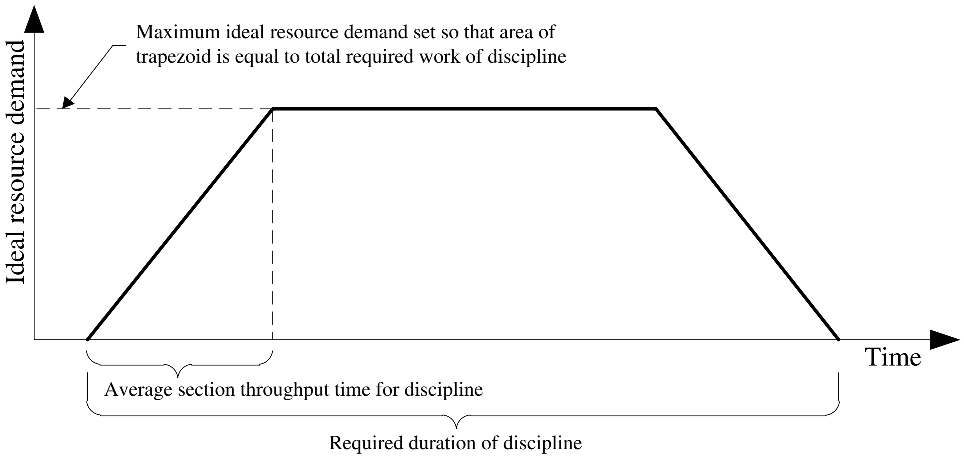


Figure 5.3: Example ideal resource demand curve

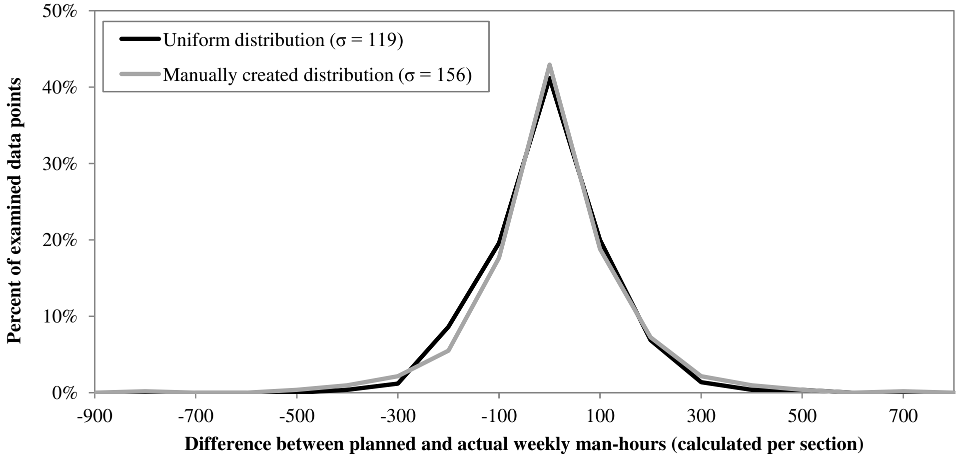


Figure 5.4: Accuracy of man-hour distributions for assembly

off does exist between them. The goal of this research is not to generate the best Section Building Plan when considering both resource leveling and outsourcing, but instead to generate a Pareto front of non-dominated schedules. This information can be used by existing section building planners in combination with their own experience to create the Section Building Plan for a given ship.

5.3 Mathematical Model

This section describes the mathematical model developed for the section building process of complex ships with the inclusion of outsourcing and outfitting. This mathematical model is based on the qualitative problem description given in the previous section. The following notation is used:

i	index used for section building tasks
j	index used for assembly and outfitting disciplines
t	index used for time
S	set of section building tasks required to build a ship
D	set of assembly and outfitting disciplines
T	set of considered time steps
a_i	duration of assembly for task i (decision variable)
p_i	duration of pre-outfitting for task i (decision variable)
b_i	duration of buffer for task i (decision variable)
o_i	outfitting indicator for task i, where o_i is 1 if i is outsourced and 0 if performed on-site (decision variable)
z_i	erection time of section associated with task i
a_{min_i}	minimum duration of assembly for task i
a_{max_i}	maximum duration of assembly for task i
p_{min_i}	minimum duration of pre-outfitting for task i
p_{max_i}	maximum duration of pre-outfitting for task i

b_{min_i}	minimum duration of buffer for task i
b_{max_i}	maximum duration of buffer for task i
κ	duration of overlap of assembly and pre-outfitting
c_j	type of discipline j, where c_j is 1 if work of j is performed during assembly and 2 if it is performed during pre-outfitting
$m_{i,j}$	required man-hours to complete all of the required work of discipline j for task i
$q_{j,t}$	ideal total resource requirement for discipline j at time t
$r_{j,t}$	achieved total resource requirement for discipline j at time t
$Z_{1,t}$	set of all tasks which are in assembly at time t
$Z_{2,t}$	set of all tasks which are in pre-outfitting at time t
$Z_{3,t}$	set of all tasks which are in either assembly or pre-outfitting at time t
h_t	number of section beds available at time t
g_i	number of section beds required by a task i, where $n_i = 0.5$ for small sections and $n_i = 1$ otherwise
O_{outs}	Outsourcing Objective
O_{res}	Resource Objective

Equation 5.1 calculates the Outsourcing Objective, which should be minimized.

$$O_{outs} = \frac{\sum\limits_{j \in D} \sum\limits_{i \in S} (m_{i,j})(o_i)}{\sum\limits_{j \in D} \sum\limits_{i \in S} (m_{i,j})} \tag{5.1}$$

Equation 5.2 calculates the Resource Objective, which should be minimized.

$$O_{res} = \sum_{j \in D} \sum_{t \in T} (q_{j,t} - r_{j,t})^2 \tag{5.2}$$

where $q_{j,t}$ is constructed using the methodology shown in Figure 5.3 and $r_{j,t}$ is calculated by Equation 5.3

$$r_{j,t} = \begin{cases} \sum\limits_{i \in Z_{1,t}} (m_{i,j}/a_i) & \text{if } c_j = 1 \\ \sum\limits_{i \in Z_{2,t}} (m_{i,j}/p_i) & \text{if } c_j = 2 \end{cases} \qquad \forall t \in T, \ \forall j \in D \tag{5.3}$$

where $Z_{1,t}$ and $Z_{2,t}$ are determined using Equations 5.4 and 5.5 respectively

$$Z_{1,t} = \{i \in S : o_i = 0 \land (z_i - b_i - p_i + \kappa - a_i) \leq t < (z_i - b_i - p_i + \kappa)\} \tag{5.4}$$

$$Z_{2,t} = \{i \in S : o_i = 0 \land (z_i - b_i - p_i) \leq t < (z_i - b_i)\} \tag{5.5}$$

Equations 5.6, 5.7, and 5.8 ensure that the duration of each section's assembly, pre-outfitting, and buffer is within the allowed limits, enforcing the Task Duration Constraints.

$$min_{a_i} \leq a_i \leq max_{a_i} \quad \forall i \in S \tag{5.6}$$

$$min_{p_i} \leq p_i \leq max_{p_i} \quad \forall i \in S \tag{5.7}$$

$$min_{b_i} \leq b_i \leq max_{b_i} \quad \forall i \in S \tag{5.8}$$

Equation 5.9 limits the number of sections that can be built on-site at each point in time, satisfying the Floor Space Constraints.

$$\sum_{i \in Z_{3,t}} g_i \leq h_t \quad \forall t \in T \tag{5.9}$$

where h_t is determined using the methodology shown in Figure 5.2 and $Z_{3,t}$ is determined using Equation 5.10

$$Z_{3,t} = Z_{1,t} \cup Z_{2,t} \tag{5.10}$$

5.4 Methodology

The NSGA-II was selected to solve the developed mathematical model because this algorithm was successfully used by the Erection Planning Method to automatically create production schedules (see Section 4.6). Section 4.4 contains additional reasons for using this algorithm. The NSGA-II, originally proposed by Deb et al. (2002), is a multi-objective genetic algorithm capable of working with continuous variables. More details regarding this algorithm are given in Section 4.4.

In a genetic algorithm, each potential solution is represented by a chromosome, and a fitness function is used to determine the quality of each chromosome. In this case, the fitness function generates a Section Building Plan and then assesses that plan based on its resource demands and outsourcing requirements. Because genetic algorithms perform poorly when the solution space is dominated by infeasible solutions, the solution representation and fitness function were designed to guarantee that every chromosome corresponds with a feasible Section Building Plan.

Figure 5.5 shows the chromosome representation used. Every section is described by four genes, where Y_{a_s}, Y_{p_s}, and Y_{b_s} are factors used to calculate the duration of assembly process, pre-outfitting process, and buffer respectively of section $i \in S$. Each section also has an outsourcing priority Y_{o_s}. Each gene can take any real value between zero and one, so that $0 \leq Y \leq 1$. Figure 5.6 describes the fitness function used to transform each chromosome into a feasible Section Building Plan and assess the quality of the plan.

Step 1 initializes the outsourcing indicator of all sections to zero, indicating that these sections are to be built on-site. The second step calculates the assembly, pre-outfitting, and buffer durations of each section based on the corresponding genes in the chromosome. These durations are calculated in a way to ensure that the Task Duration Constraints are satisfied. The space requirements of the Section Building Plan are then calculated by the third step. Step 4 terminates the fitness algorithm if the Floor Space Constraints are met. If the Floor Space Constraints are violated, step

$$[\underbrace{Y_{a_1}, Y_{p_1}, Y_{b_1}, Y_{o_1},}_{\text{Genes for section building task 1}} \underbrace{Y_{a_2}, Y_{p_2}, Y_{b_2}, Y_{o_2}}_{\text{Genes for section building task 2}} \dots \underbrace{Y_{a_n}, Y_{p_n}, Y_{b_n}, Y_{o_n}}_{\text{Genes for section building task n}}]$$

Figure 5.5: Chromosome representation

Step 1. Set $o_i = 0 \ \forall i \in S$

Step 2. Calculate the following durations $\forall i \in S$

(a) $a_i = a_{min_i} + (a_{max_i} - a_{min_i}) * Y_{a_i}$
(b) $p_i = p_{min_i} + (p_{max_i} - p_{min_i}) * Y_{p_i}$
(c) $b_i = b_{min_i} + (b_{max_i} - b_{min_i}) * Y_{b_i}$

Step 3. Calculate $Z_t \ \forall t \in T$

Step 4. If the Floor Space Constraint (Equation 5.9) is satisfied, go to step 6

Step 5. Set $o_i = 1$ for section with highest outsourcing priority Y_{o_i} which satisfies the following conditions, and then go to step 3:

(a) $o_i = 0$
(b) $i \in Z_{3,t}$ for some t where $\sum\limits_{i \in Z_{3,t}} g_i > h_t$

Step 6. Calculate O_{outs} and O_{res} using Equations 5.1 through 5.5

Figure 5.6: Fitness function

5 outsources the section with the highest outsourcing priority that contributes to the violation of this constraint. Steps 3-5 are repeated until a feasible Section Building Plan is created. The last step of the fitness function calculates the Outsourcing and Resource Objectives.

The NSGA-II parameters used for the Erection Planning Method were also used for the Section Building Planning Method: population size = 100, crossover probability = 0.9, distribution index for crossover = 20, mutation rate = 1/chromosome length, distribution index for mutation = 20, and stopping condition = 250 generations. The rational for selecting these parameters is descibed in Section 4.5. Because the performance of the genetic algorithm was satisfactory when using these parameters, no further effort was performed to optimize these parameters. However, additional improvement in both solution quality and computational time may be attainable by tuning all of the NSGA-II parameters (see Section 4.5).

5.5 Test Case

A test case was performed of a recently delivered pipelaying ship from Royal IHC, a Dutch shipbuilding group. This was done to demonstrate the feasibility of both the mathematical model and solution approach. Table 5.1 summarizes the characteristics of this test case. Input from experienced shipyard planners as well as an analysis of past section building schedules was used to set the task duration limits.

Table 5.1: Test case characteristics

Number of sections ($\|S\|$)	112
Definition of small sections ($g_s = 0.5$)	area <100 m^2
Minimum assembly duration (min_{a_s})	20 days
Maximum assembly duration (max_{a_s})	60 days
Minimum pre-outfitting duration (min_{p_s})	5 days
Maximum pre-outfitting duration (max_{p_s})	15 days
Minimum buffer duration (min_{b_s})	15 days
Maximum buffer duration (max_{b_s})	45 days
Overlap duration (κ)	5 days

Royal IHC planners had already estimated the total required man-hours for the assembly task of each section built on-site, and these predictions were used for this test case. Royal IHC had also developed a regression-based tool to predict the required assembly man-hours of a section based on its weight and type. This tool was used to estimate the required assembly man-hours for the outsourced sections of the test case. The difference between the assembly man-hour predictions of this tool and the predictions of the planners is generally less than 10%. The actual hours required to assemble the sections were not used since this information is not available when making the Section Building Plan.

Table 5.2 describes the outfitting disciplines considered in the test case. These disciplines represent the vast majority of the total outfitting work performed in the pre-outfitting phase. The installation tasks considered for each discipline are also listed in this table. Eighty percent of the total man-hours required for these tasks were assumed to occur during pre-outfitting, as suggested by Schank et al. (2005). The ship's drawings were used to determine the required number of outfitting tasks per section required for each discipline. The methodology developed by Wei (2012) was used to determine the number of man-hours required for the installation of pipe spools, HVAC ducting, and cable trays. An analysis of the recorded hours for secondary steel tasks was used to estimate the required man-hours for these tasks, and an expert opinion was used to estimate the required installation time of light fixtures.

The baseline Erection Plan created by the erection planners of the test case ship was used to determine the erection times for each section. The assumption was made that the shipyard operated two eight-hour shifts. These shifts worked for five days a week, with the exception of official shipyard holidays.

Table 5.2: Outfitting disciplines and tasks considered in test case

Discipline	Installation tasks
Piping	Spools
HVAC	Ducting and minor equipment
Electrical	Cable trays and light fixtures
Secondary steel	Foundations, stairs, ladders, platforms, and railings

5.6 Results

Figure 5.7 presents the Pareto fronts for the Resource and Outsourcing Objective for ten trials. The position of the Section Building Plan generated manually by the shipyard planners relative to the Pareto fronts is also included in this figure. This figure demonstrates that the NSGA-II produced fairly consistent results, as the Pareto fronts are roughly in the same position. Figure 5.7 also suggests that additional gains can be realized in terms of both of the examined objectives compared to the plan used by the shipyard.

Figures 5.9 through 5.13 compare the resource distribution functions of the Section Building Plan manually created by the shipyard planners to one of the most promising schedules generated by the NSGA-II. The axes labels of these figures have been replaced by normalized ones at the request of Royal IHC. The promising schedule, which is located on the Pareto front, is also included in Figure 5.7. A schedule with the same outsourcing percentage as the manually created schedule was selected

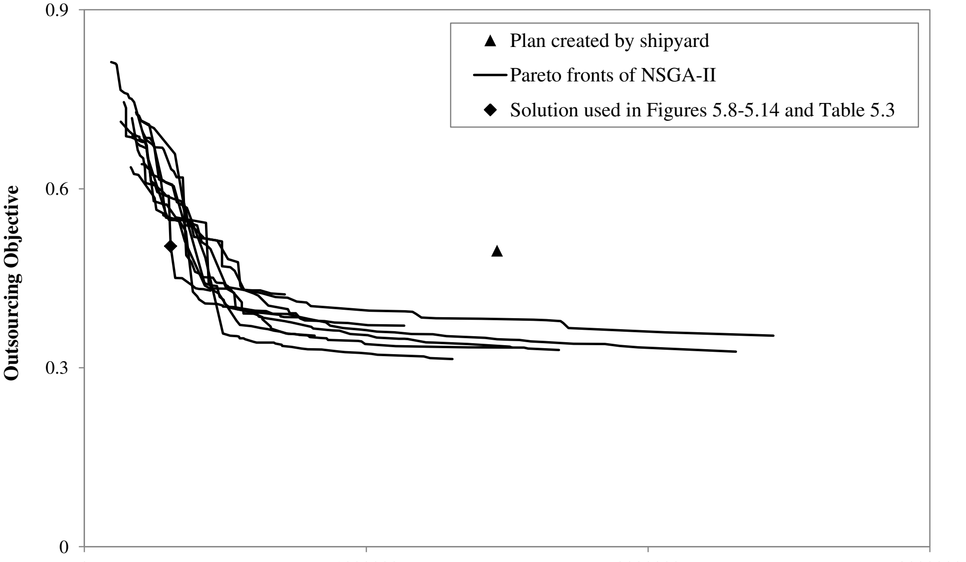


Figure 5.7: Pareto front of Resource and Outsourcing Objective for test case

for an even comparison. However, these two schedules differed substantially in their outsourcing strategy. Of the 112 sections, 37 were built on-site by both schedules and 25 were outsourced by both schedules. The outsourcing strategy differed for the remaining 50 sections. Figure 5.8 compares the percent of total workload by discipline for both section building schedules. This figure indicates that the solution produced by the NSGA-II prioritized outsourcing HVAC tasks while the shipyard planners prioritized outsourcing electrical and secondary steel work.

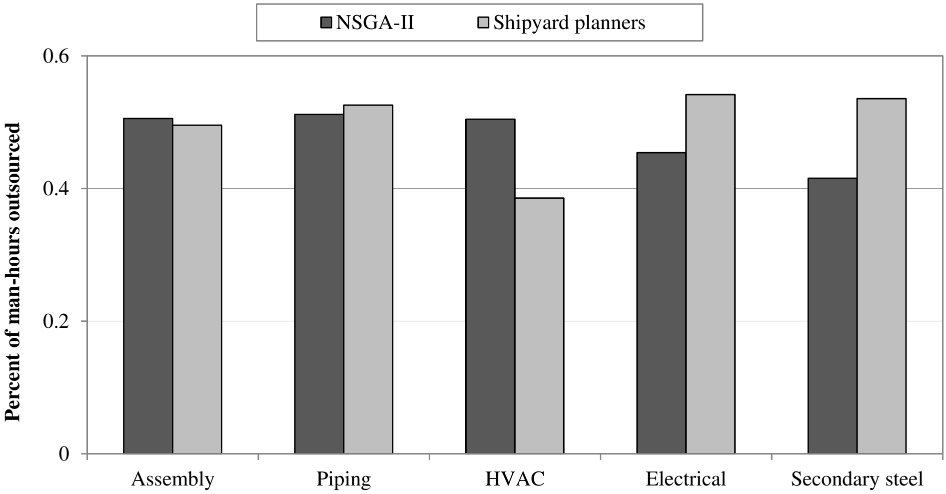


Figure 5.8: Percent of outsourced workload by discipline

Ideal resource distribution functions are also included in Figures 5.9 through 5.13 for reference. Because a different set of sections are outsourced for the two section building schedules compared in Figure 5.7, the total number of man-hours required for each discipline differs for the two schedules. This occurs because the workload is not evenly distributed between the different sections, especially for the outfitting disciplines. As a result, the ideal resource distribution functions of the two schedules also differ. Figures 5.9 through 5.13 contain the average of the two ideal resource distribution functions. In reality, the difference is so small that the ideal resource distribution functions are barely visually distinguishable from each other, differing on average by roughly 4%.

Figures 5.9 through 5.13 demonstrate that the Section Building Plan created by the NSGA-II has more even resource requirements than the plan created manually by the shipyard planners. The value of the portion of the Resource Leveling Objective calculated for each of the disciplines for both of the schedules included in Figures 5.9 through 5.13 is presented in Table 5.3. This table shows that the Section Building Plan created by the NSGA-II had more level resources than the plan created by the shipyard planners for all disciplines except piping. Table 5.3 also indicates that the greatest gains were achieved for the section assembly task, the task with by far the greatest number of required man-hours. This occurred because the NSGA-II seeks to minimize the sum of the Resource Leveling Objectives for each of the

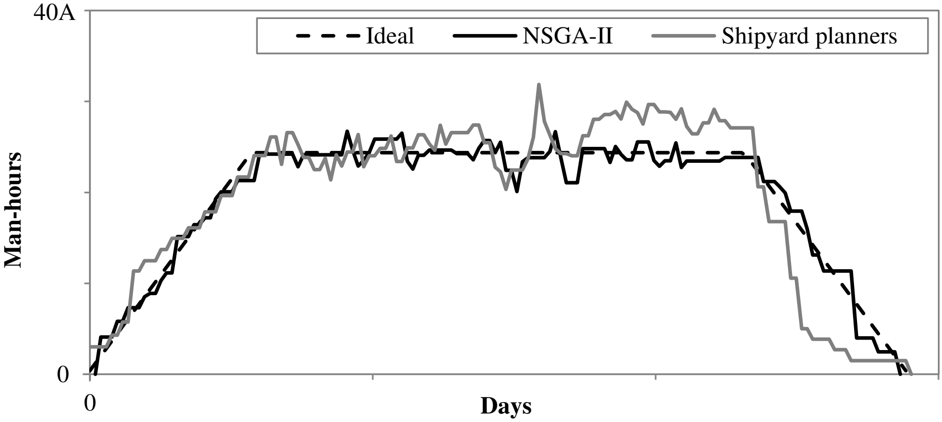


Figure 5.9: Required resources curves for assembly

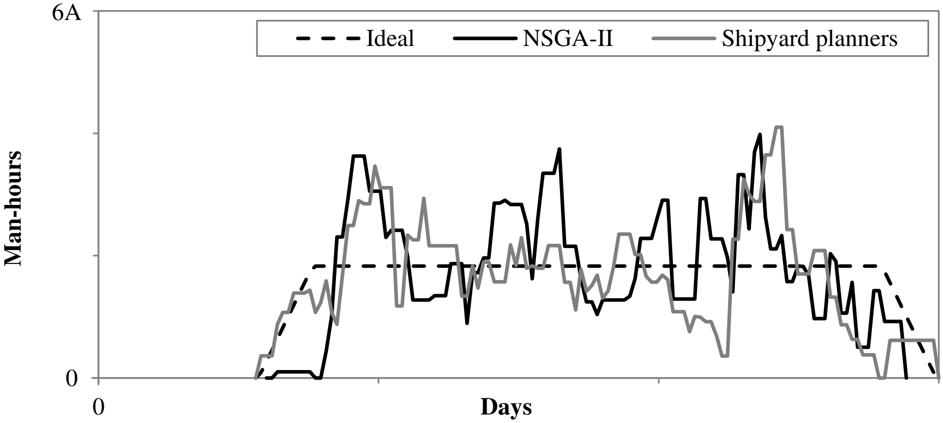


Figure 5.10: Required resources curves for piping

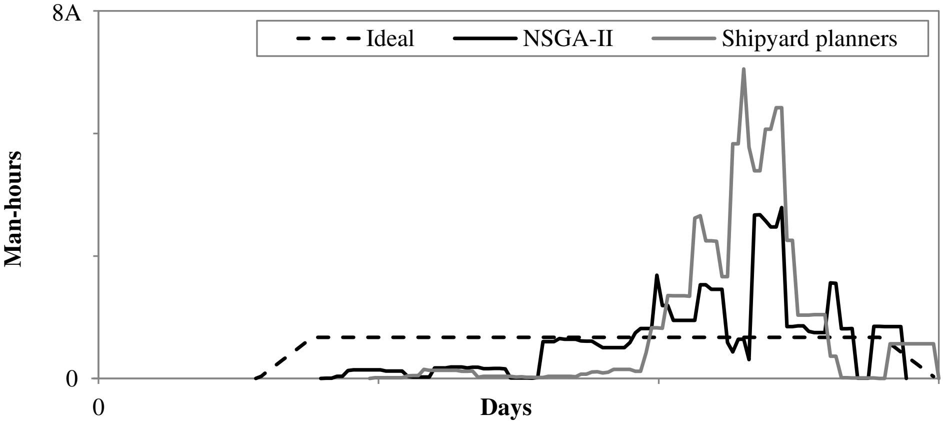


Figure 5.11: Required resources curves for HVAC

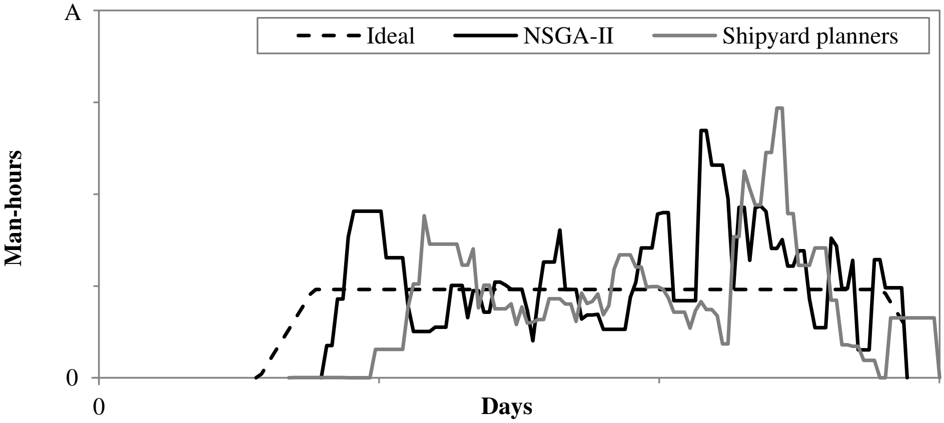


Figure 5.12: Required resources curves for electrical

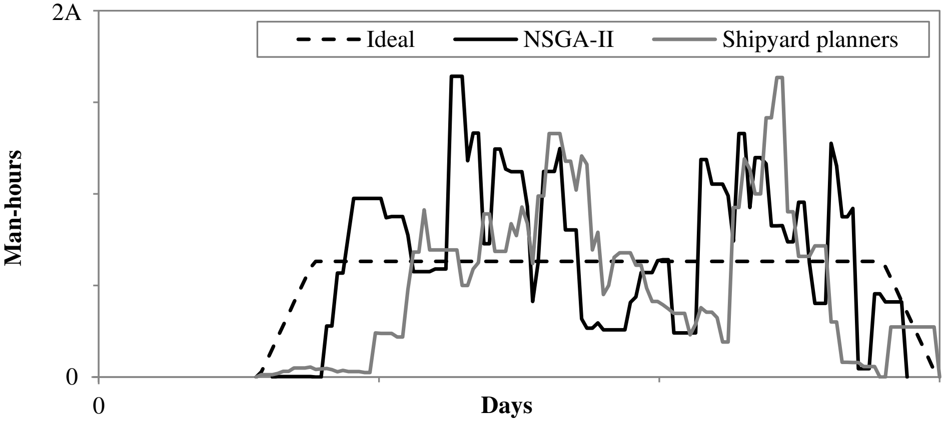


Figure 5.13: Required resources curves for secondary steel

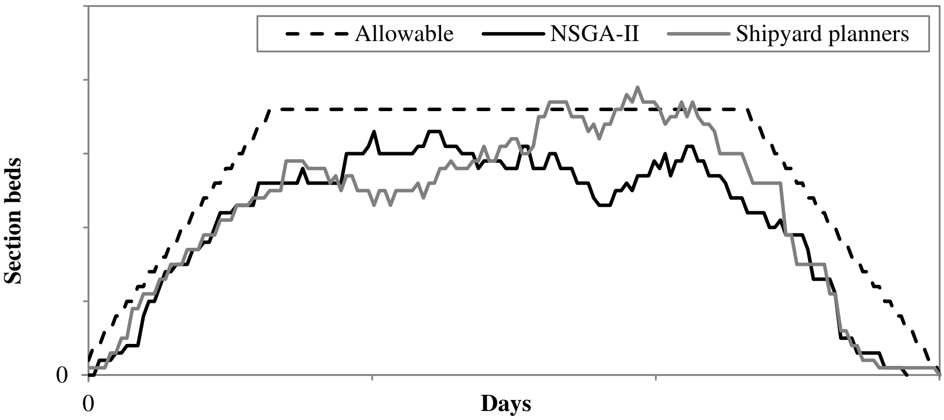


Figure 5.14: Number of section beds required

disciplines instead of the individual components. As a result more emphasis is placed on creating level resource curves for disciplines with a greater number of required man-hours. It would also be possible to steer the NSGA-II to level the resources of each discipline individually by redefining the Resource Leveling Objective as a set of separate objectives for each discipline. However, interpreting the results becomes more challenging when six different objectives must be compared. Alternatively, the NSGA-II could be steered to focus more heavily on a given discipline by increasing its weight in the Resource Objective function.

Table 5.3: Resource leveling objective per discipline

Discipline	Assembly	Piping	HVAC	Electrical	Secondary steel
NSGA-II	184000	71500	35700	1760	13600
Actual	1260000	58100	128000	2210	14000

Figure 5.11 indicates that neither the plan generated by the NSGA-II nor the plan created by the shipyard planners were able to create a particularly even workload for the HVAC discipline. Both schedules result in a high peak in workload in the third quarter of production. This occurs as a result of the Erection Plan used in this test case, which requires that most of the HVAC intensive sections be erected during this quarter. To alleviate this uneven HVAC workload, the Erection Plan itself needs to be altered. However, Figure 5.11 indicates that the NSGA-II created a significantly more even HVAC workload distribution than the real Section Building Plan created manually by the shipyard planners.

Figure 5.14 depicts the number of section beds required by both schedules over the process duration. The axes labels have been removed from this figure at the request of Royal IHC. This figure shows that the Section Building Plan created by the shipyard planners slightly violates the Floor Space Constraint at some points. When asked about this violation, the planners indicated that the space constraint was at times flexible, but local factors (such as complexity of required work, availability of overtime, etc.) need to be taken into account when violating this constraint. In the future, the methodology presented in this chapter could be expanded to take into account the flexible nature of this constraint. However, Figure 5.7 proves that improvements are still obtainable while applying this constraint stringently.

The optimization was performed using MATLAB and run on a 64-bit PC with 16 GB RAM and an 8x 3.50 GHz processor. A single trial required roughly two minutes to run.

5.7 Validation

The Section Building Planning Method was validated using the same framework employed to validate the Erection Planning Method, the Validation Square. Section 4.7 describes the Validation Square and details how it was used to assess the Erection Planning Method. Only the portions of the validation process specific to the Section Building Planning Method are described in this section. The rest of the validation process was identical to the one described in Section 4.7.

Validation sessions with experienced shipbuilding personnel from section building were conducted to assess the constructs of the Section Building Planing Method. Appendix B contains a description of these sessions' participants. These participants provided the following feedback regarding the constraints and objectives used to model the section building process:

- The painting of sections should be included in the Section Building Plan. Furthermore, some outsourced sections are still painted on-site.
- A constraint should be added to indicate when a section must be built on-site. This is required for some complex, critical sections.
- The minimum time for assembling a section should be five weeks instead of four weeks.
- An additional constraint should be added to ensure that required engineering work is completed in time.
- The minimum buffer duration for some sections can be as little as one week since it is possible to rush sections through the paint hall. However, this can only be done for a few sections each project.
- Some shipyards use the concept of floor area instead of section beds to limit the number of sections that can be built simultaneously.

The participants were also asked if the required input information for the Section Building Planning Method was available at the beginning of the section building planning process. The participants stated that initially only the required man-hours for assembly and outfitting are not available. Crude estimation techniques are used to estimate these man-hours. These values are later refined as more geometric data becomes available from engineering.

With the exception of the items described in this section, the Section Building Planning Method satisfied the individual constructs of the Validation Square. Because of the flexible nature of the solution technique of the Section Building Planning Method, it is straightforward to add the additional constraints suggested in the validation sessions. The shipbuilding community is also actively researching methods for better estimating the required workload for assembly and pre-outfitting, such as the works of Colthoff (2009), Vlaar (2010), and Gregory (2015).

5.8 Implementation

The method developed for automatically generating a Section Building Plan described in this chapter could be implemented in a shipyard in the same way as the method developed for automatically generating an Erection Plan described in the previous chapter (see Section 4.8). For the shipyard building the test case ship, it would be fairly easy to integrate the Section Building Planning Method into the current work flow of the planners. The section building planners of this shipyard already use a crude Microsoft Excel based tool to generate an initial Section Building Plan. This tool takes the section characteristics and Erection Plan as input and builds a Section

Building Plan using rules of thumb to estimate task durations. The planners then manually select which sections to outsource and adjust the plan by hand until the space constraints are satisfied. This process is both time consuming and does not consider the effect of outfitting. Furthermore, level resource curves over the entire duration of the project are rarely achieved. The developed methodology is a viable improvement of such a tool.

5.9 Conclusion

The Section Building Planning Method is developed in this chapter. This module of the Integrated Shipbuilding Planning Method automatically generates a Section Building Plan for the construction of a complex ship. The mathematical model of the section building process used as a basis of this method differs from previously published works due to the inclusion of outsourcing and outfitting. A genetic algorithm, specifically the NSGA-II, was used to find an optimal solution to the developed mathematical model. The goal of the optimization was to minimize the amount of outsourced work and variations in the resource requirements throughout the shipbuilding process. Due to the multi-objective nature of the mathematical model, the optimization created a Pareto front of possible solutions instead of a single, best solution. This set of section building schedules can be used to enhance the decision making abilities of existing shipyard planners.

A test case was performed on a recently delivered pipelaying ship from a Dutch shipyard to demonstrate the feasibility of both the proposed mathematical model and solution technique. The test case showed it was possible to quickly generate a diverse set of high-quality section building schedules. The quality of some of these schedules exceeded that of those manually created by the shipyard planners with respect to both objectives. The Section Building Planning Method was validated using the Validation Square framework and the implementation of the method in a shipyard was discussed.

The Erection Plan was used as an input for the Section Building Planning Method. Currently, the Erection Plan is being manually generated by experienced shipyard planners (similar to how the Section Building Plan is currently generated). However, the Erection Planning Method, developed in the previous chapter, could be used to automatically create the erection times of each section. Because of the interdependencies between the section building and erection processes, optimizing these processes concurrently can lead to even greater benefits than examining only the section building process. These two processes are considered simultaneously by the Combined Erection and Section Building Planning Method, which is developed in the next chapter.

Chapter 6

Combined Erection and Section Building Planning Method

This chapter develops the Combined Erection and Section Building Planning Method. This method executes the Erection Planning Method (described in Chapter 4) and the Section Building Planning Method (described in Chapter 5) concurrently. As described in Section 2.2, shipyard planners generally consider the section building and erection processes sequentially. Because the erection process limits the capacity of a shipyard, the planners first create the Erection Plan. The erection dates of each section specified in the Erection Plan are then used as the primary input for creating the Section Building Plan.

Considering these two processes simultaneously offers several advantages. First, sacrificing some performance of the erection process might vastly improve the performance of the section building process. For example, it is beneficial for the erection process to initially erect a majority of the double bottom sections to improve the slipway outfitting process. However, these sections generally contain no ducting. Therefore, it benefits the pre-outfitting of the HVAC discipline to erect a section full of ducting early in the process. These types of trade-offs cannot be seen unless an integrated planning approach is implemented.

Secondly, the effects of building blocks can be included. Blocks are groups of sections that are welded together in the section building area prior to erection. Building blocks improves the erection process since less total work is performed on the slipway, often increasing the capacity of the shipyard. However, building blocks requires a portion of a shipyard's section building floor area to be temporarily converted to block building floor area. This can have a negative impact on the outsourcing and resource leveling characteristics of section building. The combined model developed in this chapter can also be used to asses different scenarios related to block building (see Section 8.1).

The combined section building and erection model (CM) is based on the erection planning model (EM) and the section building planning model (SM) developed in the previous two chapters. Although it was possible to implement the majority of the constraints of the EM and SM directly in the CM, some of these equations required minor modifications. It was also necessary to add additional constraints to link the two models together and to account for the block building process. The two Resource Objectives of the EM and SM were combined to form a single combined Resource Objective. This combined objective was then used along with a modified version of the Outfitting Objective of the EM and the Outsourcing Objective of the SM to assess the quality of the production schedules created by the CM.

A methodology was also developed to find optimized solutions for the CM. This methodology is an expansion of those developed for the EM and SM described in the previous two chapters. A test case of a pipelaying ship recently built at a Dutch shipyard was used to demonstrate the feasibility of the CM and the developed solution technique.

This chapter first presents a literature review, after which a qualitative description of the combined erection and section building process is given. The development of the CM and solution technique are then described. Next, the test case used to analyze the Combined Erection and Section Building Planning Method is presented. The chapter concludes with a discussion about validation and implementation.

6.1 Literature Review

Although literature contains numerous research attempting to optimize the planning of the erection and section building process (see Sections 4.1 and 5.1), only one example was found to include both process, the Daewoo Shipbuilding Scheduling Project (Lee et al., 1997). This paper describes separate modules developed for a large Korean shipyard to schedule the erection process, curved block building process, and paneled block building process. An additional module was also developed to estimate required man-hours. The modules rely on constraint directed graph search, neural networks, and custom heuristics to find optimal solutions.

However, in this project the planning of the erection process was still leading, and its optimization is done independently beyond considering the capacity limits of the section building process. Problems found while developing the Section Building Plan stemming from poor consideration of this process while creating the Erection Plan are flagged. Shipyard planners then manually resolved these problems. Not only does the Daewoo Shipbuilding Scheduling Project fail to fully integrate the optimization of the erection and section building processes, but it is also heavily focused on the needs of large shipyards building simple ship types. For example, the outfitting process is completely excluded. Therefore, the methods of this research could not be directly applied.

6.2 Problem Description

The following section describes the additional constraints required to combine the EM and SM developed in the previous two chapters to form the CM. Unless specifically mentioned, the constraints and objectives of both processes described in Sections 4.2 and 5.2 are also included in the CM. The most important aspect of the shipbuilding process, which is included in the combined model but was excluded from the separate models, is block building. Blocks are sets of sections welded together into a single unit prior to erection. From the perspective of the EM, no difference exists between blocks and sections, as both units represent erection tasks. Blocks can expedite the erection process since work is moved away from the slipway, which is especially useful for shipyards where the slipway is the bottleneck. The dimensions and weight of blocks produced at a shipyard are limited by the capabilities of the slipway gantry crane.

Unlike typical erection tasks, the production of blocks can be outsourced. This allows a shipyard to outsource some portion of the erection man-hours of a project. If the production of a block is outsourced, the assembly of all sections composing the block should also be outsourced to prevent unnecessary transportation of sections. However, if a block is built on-site it is still possible to outsource the assembly of the sections composing the block.

Figure 6.1 describes an example Erection and Section Building Plan for the production of two example blocks. The production of block A is outsourced, and therefore only the erection of this block is included in the schedule. Block B is produced on-site, where sections $B.1$ and $B.2$ are also produced on-site while sections $B.3$ and $B.4$ are outsourced. Figure 6.1 illustrates that the construction process of each block is itself a miniature erection process. Therefore, the steel-related constraints that govern the erection process (Vertical Feasibility Constraints, Fixing Time Constraints, etc.) are also present in the block production process. Because blocks are generally created from relatively sparsely outfitted sections, such as accommodation sections, the outfitting-related constraints of the erection process (Large Equipment Constraints and Outfitting Time Constraints) are usually not required.

The on-site production of blocks interacts with the EM in two main ways. First, the same gantry crane that is used to erect sections and blocks on the slipway is also used for the placing tasks of the block production process. Therefore, the equation that enforces the Crane Time Constraints of the EM must be modified for the CM to also include the placing tasks of blocks that are built on-site. Second, the Resource Objective of the EM must be modified to include block production tasks since the the same group of workers who perform erection tasks also perform the on-site block building tasks.

Building blocks also interacts with the SM. When blocks are built on-site, they are assembled in the same area of the shipyard where section building takes place. This means that the number of section beds available for the section building process is reduced each time a block is built on-site. This interaction is exaggerated because blocks are generally large, meaning that multiple section beds are required for each block. As a result, the on-site production of blocks limits the capacity of the section building process. The Floor Area Constraints of the SM must be modified in the CM to account for block production. Additionally, the Outsourcing Objective of the SM should be modified to take into account the outsourcing of the block-related man-hours.

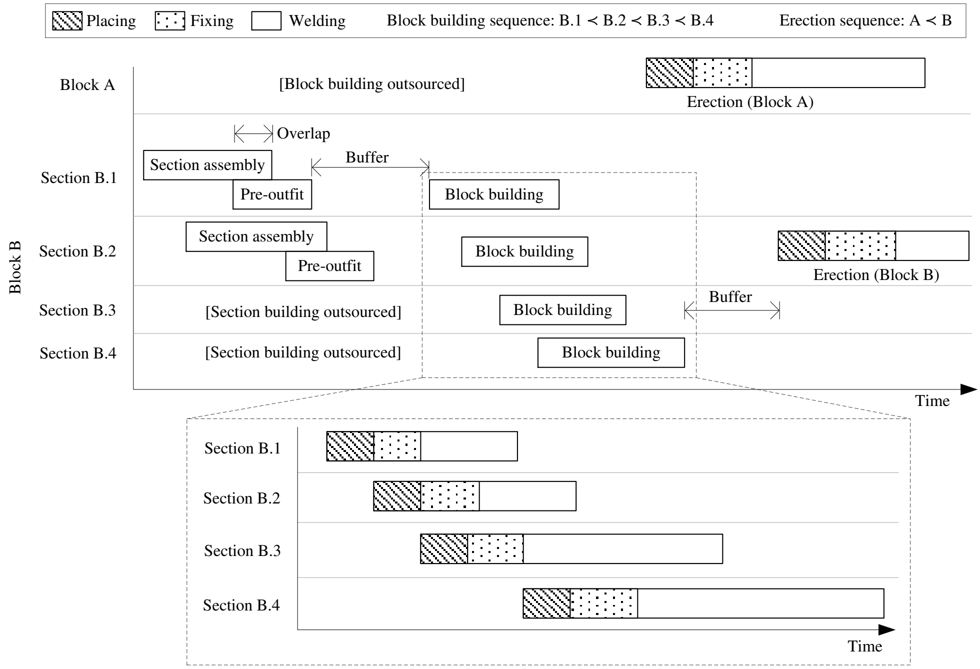


Figure 6.1: Erection and Section Building Plan for two example blocks

6.3 Mathematical Model

This section describes the mathematical model developed for the combined erection and section building process for complex ships. This model builds upon the EM and SM developed in the previous two chapters. Unless explicitly stated, the equations of the EM and SM are also included in the combined model. Variables which are taken directly from one of the other two models are indicated in their definition. The following notation is used:

i	index used for tasks
j	index used for tasks
k	index used for blocks
l	index used for disciplines
n	index used for block building sequences
t	index used for time
t_0	start time of erection process (from EM)
t_f	finish time of erection process (from EM)
T_E	set of considered time steps for erection process (T from EM)
T_S	set of considered time steps for section building process (T from SM)
E	set of erection tasks (from EM)

S	set of section building tasks (from SM)
S_B	set of section building tasks where the section constructed is part of a block, where $S_B \subseteq S$
S_E	set of section building tasks where the section constructed is directly erected, where $S_E \subseteq S$
D	set of assembly and outfitting disciplines (from SM)
K	set of blocks
B	set of block building tasks required to build a ship
B_k	set of block building tasks required for block k, where $B_k \subseteq B$
x_i	start time of task i (decision variable)
y_i	finish time of task i (decision variable)
o_i	outfitting indicator for task i, where o_i is 1 if i is outsourced and 0 if performed on-site (decision variable) (from SM for $i \in S$)
w_i	weight of section associated with task i
δ_i	duration required to place section for task i
m_i	number of man-hours required for task i, used for erection tasks that only require a single discipline
$m_{i,l}$	required man-hours to complete all of the required work of discipline l for task i (from SM)
d_i	minimum duration of task i
μ_i	unit associated with a task, where μ_i is a section for $i \in S$ and $i \in B$, and μ_i is either a block or section for $i \in E$
$f_{i,j}$	duration required for fixing section associated with task i before section associated with task j can be erected, 0 if sections are non-adjacent or not part of the same block
$\xi_{i,j}$	joining circumference between sections associated with task i and j, 0 if sections are non-adjacent or not part of the same block
ϵ	minimum buffer time required between the completion of a block and its erection
Δ_t	set of erection tasks that are placing sections on the slipway at time t (from EM)
Ω_t	set of erection tasks occurring at time t (from EM)
Θ_t	set of block building tasks whose sections have already been placed at time t
Γ_t	set of block building tasks that are placing sections at time t
Υ_t	set of block building tasks occurring at time t
Ξ_t	set of blocks being assembled at time t
N_k	set of all feasible block building sequences for block k
P_n	set of start-finish precedence constraints required for block building sequence n
(i, j)	precedence constraint between tasks i and j
$Z_{3,t}$	set of all section building tasks that are in either assembly or pre-outfitting at time t (from SM)

h_t	number of section beds available at time t (from SM)
g_i	number of section beds required by a task i, where $n_i = 0.5$ for small sections and $n_i = 1$ otherwise (from SM)
g_k	number of section beds required by block k
q	ideal total resource requirement at any point in time for erection and block building tasks
r_t	achieved total resource requirement at time t
$O_{res(E)}$	Resource Objective for erection and block building tasks
$O_{res(S)}$	Resource Objective for section building tasks (O_{res} from SM)
$O_{res(C)}$	combined Resource Objective
O_{outs}	combined Outsourcing Objective
β_0	constant parameter of man-hours regression
β_1	weight parameter of man-hours regression
β_2	joining circumference parameter of man-hours regression

Equation 6.1 links the erection time of the section assembly tasks of the SM to the corresponding start times of the erection tasks in the EM for all sections which are not part of a block.

$$z_i = x_j \qquad \forall i \in S_E, j \in E, \mu_i = \mu_j \tag{6.1}$$

The start time of the block building tasks is linked with the erection time of the corresponding section assembly tasks of the SM for all sections which are part of blocks by Equation 6.2.

$$z_i = x_j \qquad \forall i \in S_B, j \in B, \mu_i = \mu_j \tag{6.2}$$

Equation 6.3 calculates the number man-hours required for each block building task.

$$m_i = \beta_0 + \beta_1 w_i + \beta_2 \sum_{j \in \Theta_t} \xi_{i,j} \qquad \forall i \in B, t = x_i \tag{6.3}$$

where Θ_t is calculated using Equation 6.4

$$\Theta_t = \{i \in B : x_i + \delta_i \leq t\} \tag{6.4}$$

Equation 6.5 determines the total resource demand of all tasks requiring erection resources (erection and block building). This demand corresponds with perfectly level resource curves. Equation 6.6 replaces Equation 4.3 from the EM.

$$q = \frac{\sum\limits_{i \in E} m_i + \sum\limits_{j \in B} m_j(1 - o_j)}{t_f - t_0} \tag{6.5}$$

The total erection resource requirements (from erection and block building) are calculated for each time step using Equation 6.6, which replaces Equation 4.4 from the EM.

$$r_t = \sum_{i \in \Omega_t} \frac{m_i}{y_i - x_i} + \sum_{j \in \Upsilon_t} \frac{m_j(1-o_j)}{y_j - x_j} \qquad \forall t \in T_E \tag{6.6}$$

where Equation 6.18 calculates Υ_t

$$\Upsilon_t = \{i \in B : x_i < t \leq y_i\} \tag{6.7}$$

Equation 6.8 determines the Resource Objective for the erection discipline. This equation replaces Equation 4.6 from the EM.

$$O_{res(E)} = \sum_{t \in T_E} (q - r_t)^2 \tag{6.8}$$

The combined Resource Objective is calculated by Equation 6.9. This equation combines the Resource Objective from the erection discipline with that of the section assembly and outfitting disciplines calculated by the SM.

$$O_{res(C)} = O_{res(E)} + O_{res(S)} \tag{6.9}$$

Equation 6.10 determines the combined Outsourcing Objective by calculating the total percent of man-hours that are outsourced across all disciplines. This objective should be minimized and replaces Equation 5.1 from the SM.

$$O_{outs} = \frac{\sum\limits_{l \in D} \sum\limits_{i \in S} (m_{i,l})(o_i) + \sum\limits_{j \in B} (m_j)(o_j)}{\sum\limits_{l \in D} \sum\limits_{i \in S} (m_{i,l}) + \sum\limits_{j \in B} (m_j)} \tag{6.10}$$

Because the block building process does not directly affect slipway outfitting, the Outfitting Objective is not modified. This objective is still calculated by Equation 4.8 of the EM. Equation 6.11 enforces that the duration of each block building task is longer than its minimum duration.

$$y_i - x_i \geq d_i \qquad \forall i \in B \tag{6.11}$$

Equation 6.12 ensures that the block building tasks of each block are finished sufficiently before the erection task of that block (taken from the EM).

$$max(y_i, \forall i \in B_k) + \epsilon \leq x_j \qquad \forall k \in K, j \in E : \mu_j = k \tag{6.12}$$

The Fixing Time Constraints between the block building tasks are enforced by Equation 6.13.

$$x_j + f_{i,j} \leq x_i \qquad \forall i \in B, \forall j \in \Theta_{x_i} \tag{6.13}$$

Equation 6.14 guarantees that a feasible block building sequence is followed for each block.

$$x_i < x_j \quad \forall (i,j) \in P_n, \exists n \in N_k, \forall k \in K \tag{6.14}$$

Equation 6.15 enforces the Crane Time Constraints for the combined model, replacing Equation 4.13 from the EM.

$$|\Delta_t| + |\Gamma_t| \leq 1 \qquad \forall t \in T \tag{6.15}$$

where Γ_t is determined using Equation 6.16

$$\Gamma_t = \{i \in B : x_i \leq t \leq x_i + \delta_i\} \tag{6.16}$$

The Floor Area Constraint for the combined model is enforced by Equation 6.17. This equation replaces Equation 5.9 from the SM.

$$\sum_{i \in Z_{3,t}} g_i + \sum_{k \in \Xi_t} g_k \leq h_t \quad \forall t \in T_S \tag{6.17}$$

where Equation 6.18 calculates Ξ_t

$$\Xi_t = \{k \in B : min(x_i, \forall i \in B_k) < t \leq max(y_i, \forall i \in B_k)\} \tag{6.18}$$

Equation 6.19 guarantees that all block building tasks of the same block are either outsourced or performed on-site.

$$o_i = o_j \qquad \forall i \in B, \forall j \in B, \{i, j\} \subseteq B_k, \exists k \in K \tag{6.19}$$

Equation 6.20 ensures that whenever a block building task is outsourced the corresponding section building tasks are also outsourced.

$$o_i = 1 \qquad \forall i \in S, \forall j \in B, \mu_i = \mu_j, o_j = 1 \tag{6.20}$$

6.4 Methodology

The NSGA-II was selected to solve the CM for the same reasons this method was used to optimize the EM and SM (see Section 4.4). Furthermore, the NSGA-II was capable of finding high-quality solutions to the EM and SM in a reasonable computational time (see Sections 4.6 and 5.6). Section 4.4 contains a brief qualitative description of this algorithm, and Deb et al. (2002) contains its complete formulation.

Figure 6.2 describes the chromosome representation used. This figure indicates that the chromosome is composed of three regions. The first and second regions are composed of the genes required to solve the EM and SM respectively (shown in Figures 4.5 and 5.5). The third region contains the additional genes necessary for scheduling block building tasks. Each block $k \in K$ is assigned a gene, Z_{o_k}, which is used to determine if the block is outsourced or built on-site. An additional three genes are added for each section $i \in B_k$ composing the block: $Z_{p_{k_i}}$, $Z_{w_{k_i}}$, and $Z_{d_{k_i}}$. These three genes mirror those required to schedule an erection task seen in the middle region of the chromosome.

The fitness function used to convert each chromosome into an Erection and Section Building Plan is described in Figure 6.3. The following additional notation is used, where FFS is the fitness function developed to solve the SM and FFE is the fitness function developed to solve the EM (shown in Figures 4.6 and 5.6):

s	selected block

a	selected block building task
h'_t	number of section beds available at time t for the section building process
O_{res}	Resource Objective calculated by FFE
M	arbitrarily large number

The first step of the fitness function creates an Erection Plan using the FFE. The Resource Objective of the erection tasks and Outfitting Objective are also calculated. The feasibility of the generated Erection Plan is checked in the second step. If the plan is not feasible, a penalty value is assigned to the combined Resource Objective and the Outsourcing Objective, and the fitness function terminates. The FFE already assigns a penalty value to the Outfitting Objective in the case of an infeasible schedule.

Steps 3 through 8 schedule the required block building tasks. These tasks are scheduled in reverse chronological order based on the erection date of the blocks. Step 4 uses the outsourcing gene of a block to determine if that block is outsourced or built on-site. If the block is outsourced, the outsourcing indicators of the block building tasks and section building tasks of all sections belonging to that block are set to one. If the block is built on-site, the first nine steps of the FFE are used to schedule the block building process of that block. It is possible to use the FFE to schedule block building tasks since building a block is essentially a miniature section erection process. The inputs of the FFE are adjusted to match the characteristics of the block.

After the building of a block is scheduled, steps 5 through 7 check if the gantry crane is available for each of the newly scheduled block building tasks. This is done to ensure that the Crane Time Constraints are met. If the gantry crane is not available for a given block building task, the block building schedule of that block is shifted forward until the Crane Time Constraints are satisfied.

Step 9 calculates the number of section beds available for the section building process by subtracting the number of section beds required for the block building tasks performed on-site from the total number of available section beds. The tenth step creates a Section Building Plan by following the first five steps of the FFS. The Resource Objective of the section building process is calculated using the sixth step of the FFS in step 11. Step 12 uses this Resource Objective as well as the characteristics of the block building and erection processes to calculate the combined Resource Objective. The final step of the fitness function calculates the Outsourcing Objective of the CM.

The same NSGA-II settings were used to solve the CM as those used to solve the EM and SM: population size = 100, crossover probability = 0.9, distribution index for crossover = 20, mutation rate = 1/chromosome length, distribution index for mutation = 20, stopping condition = 250 generations. Section 4.4 justifies the selection of these parameters and suggests how to tune the parameters to improve the performance of the algorithm.

6.5 Test Case

A test case was performed to assess the developed mathematical model and solution technique for the combined plan of the erection and section building process. This test

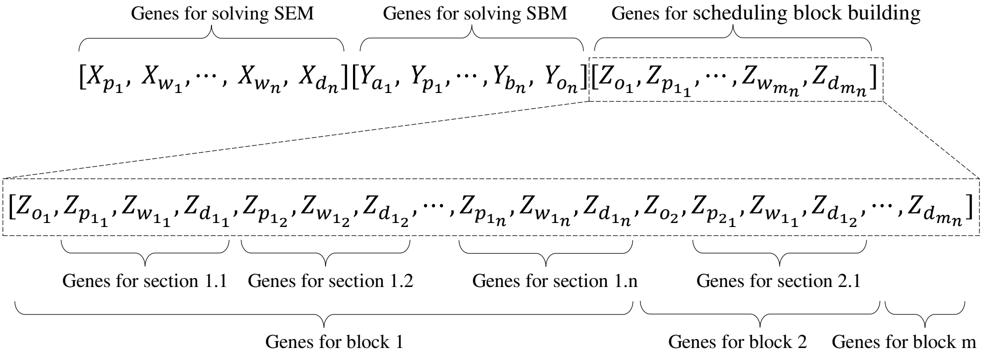


Figure 6.2: Chromosome representation

case examines the construction of a pipelaying ship recently built in the Netherlands. The same test case ship was used to evaluate the Erection Planning Method and Section Building Planning Method developed in the previous two chapters. Therefore, the test case descriptions provided in Sections 4.5 and 5.5 also apply to the test case presented in this chapter. Table 6.1 contains additional relevant characteristics of the test case.

Table 6.1: Test case characteristics

Number of blocks ($\lvert K\rvert$)	4
Number of block building tasks ($\lvert B\rvert$)	18
Buffer between block building and erection (ϵ)	15 days
Section beds required by a block (g)	2

6.6 Results

The developed methodology was implemented using MATLAB and ten trials were performed for the test case ship on a 64-bit PC with 16 GB RAM and an 8x 3.50 GHz processor. Two seconds were required to create and evaluate each generation. Overall, a total computation time of nine minutes was required for each trial.

Figure 6.4 compares the Pareto fronts of the Resource and Outsourcing Objectives created using the developed methodology to the production schedule created manually by the shipyard planners. The Pareto fronts shown in this figure are 2D representations of the 3D Pareto surface generated by the NSGA-II. This is done to allow for an easy visual comparison. In this figure, only solutions with a value for the Outfitting Objective less than or equal to the actual plan used are included. Therefore, all solutions included in the Pareto fronts shown in this figure are at least as good as the actual solution with respect to the objective not explicitly shown in the figure. Figure 6.4 shows that for all ten trials, the developed methodology was able to find solutions of higher quality with respect to both the Resource and Outsourcing Objectives than the plan actually implemented by the shipyard. However, the NSGA-II

```
Step 1.  Calculate $O_{res}$ and $O_{outf}$ using FFE
Step 2.  If $O_{res} \geq M$ and $O_{outf} \geq M$
             $O_{res(C)} = O_{res}$, $O_{outs} = M$, skip remaining steps
Step 3.  Select unscheduled block $s \in K$ with latest erection date
Step 4.  If $Z_{o_s} \leq 0.5$
             $o_i = 1 \quad \forall i \in B_s$
             $o_j = 1 \quad \forall j \in S, \forall i \in B_s, \mu_i = \mu_j$
         else
             Follow steps 1-9 of FFE with the following inputs:
             $E = B_s$, $N = N_s$, $X_{p_n} = Z_{p_{sn}}$, $X_{w_n} = Z_{w_{sn}}$, $X_{d_n} = Z_{d_{sn}}$
Step 5.  Select $a \in B_s$ with latest block building date
Step 6.  If $\exists t$ where $|\Delta_t| + |\Gamma_t| > 1$ and $x_a \leq t < x_a + \delta$
             Shift $i$ forward, where $i \in B_s$ and $x_i \leq x_a$
Step 7.  Repeat steps 5 through 6 for each task in $B_s$
Step 8.  Repeat steps 3 through 7 for each block in $K$
Step 9.  Set $h'_t = h_t - \sum_{k \in \Xi_t} g_k \quad \forall t \in T_S$
Step 10. Follow steps 1-5 of FFS to create the Section Building Plan, using $h'_t$
         instead of $h_t$
Step 11. Calculate $O_{res(S)}$ using step 6 of FFS
Step 12. Calculate $O_{res(C)}$ using Equations 6.3 trough 6.9
Step 13. Calculate $O_{outs}$ using Equation 6.10
```

Figure 6.3: Fitness function

did not produce particularly consistent results as the best front had objective values of roughly 50% less than the worst front. The performance and consistency of the NSGA-II can be improved by tuning the parameters used by the algorithm (see Section 4.4 for a suggested methodology).

Figures 6.5 and 6.6 present the same information as Figure 6.4, but for the other two pairs of objectives: Figure 6.5 examines the Resource and Outfitting Objectives, and Figure 6.6 examines the Outfitting and Outsourcing Objectives. These two figures display a similar trend as Figure 6.4 where the developed methodology found solutions of superior quality to the plan used by the shipyard for all trials. These three figures also show the objective values of a selected solution created by the NSGA-II.

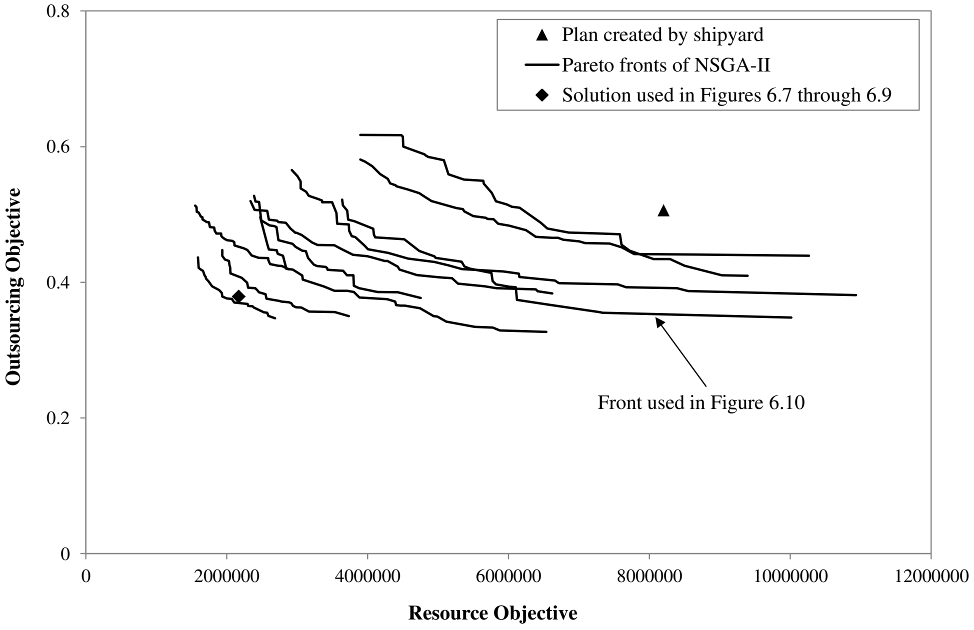


Figure 6.4: Pareto fronts for test case ship, $O_{outf} \leq 0.307$

Although this solution is not a member of any of the Pareto fronts shown in Figures 6.4 through 6.6, the selected solution was a member of the 3D Pareto surface of the trial that produced the best Pareto front shown in these figures. This solution was selected because it had extremely good performance with respect to all three objectives. The selected solution is compared to the Erection and Section Building Plan created manually by the shipyard planners in Figures 6.7 through 6.9 to indicate the potential improvements possible with regards to each of the objectives.

The total combined resource requirements of the Erection and Section Building Plan used for the test case ship and the selected solution created by the NSGA-II are presented in Figure 6.7. The axes labels have been removed from this figure at the request of Royal IHC. This figure includes both the ideal resource demand curves, which correspond to a Resource Objective of zero, and the resource demand curves achieved by the production schedules. Although the total resource demands do not directly relate to the Resource Objectives (since the objective is first calculated independently for each discipline and then summed), these curves provide a good indication about the resource utilization. Figure 6.7 indicates that total resource demand curve of the selected solution more closely follows the ideal resource demand curve. The quality of the schedule created by the shipyard planners was particularly poor during the middle of the process, where significant additional resources were required, and the end of the process, where only a third of the ideal resource levels were required. Furthermore, this figure shows that the total resource levels required for the selected solution were roughly 15% higher because more of the total workload is performed on-site for this plan. The Outsourcing Objective of both production schedules also reflects this trend.

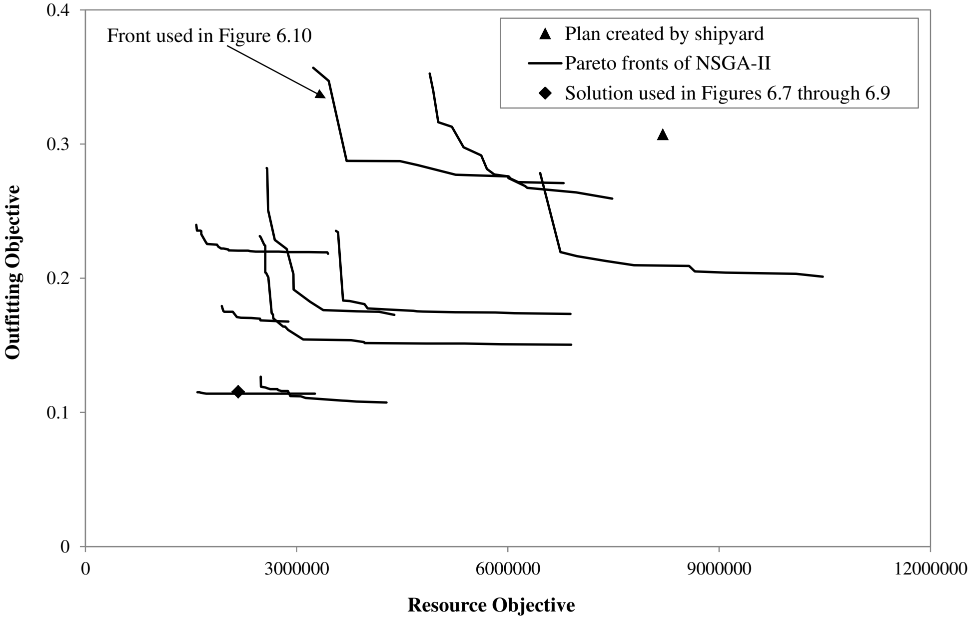


Figure 6.5: Pareto fronts for test case ship, $O_{outs} \leq 0.506$

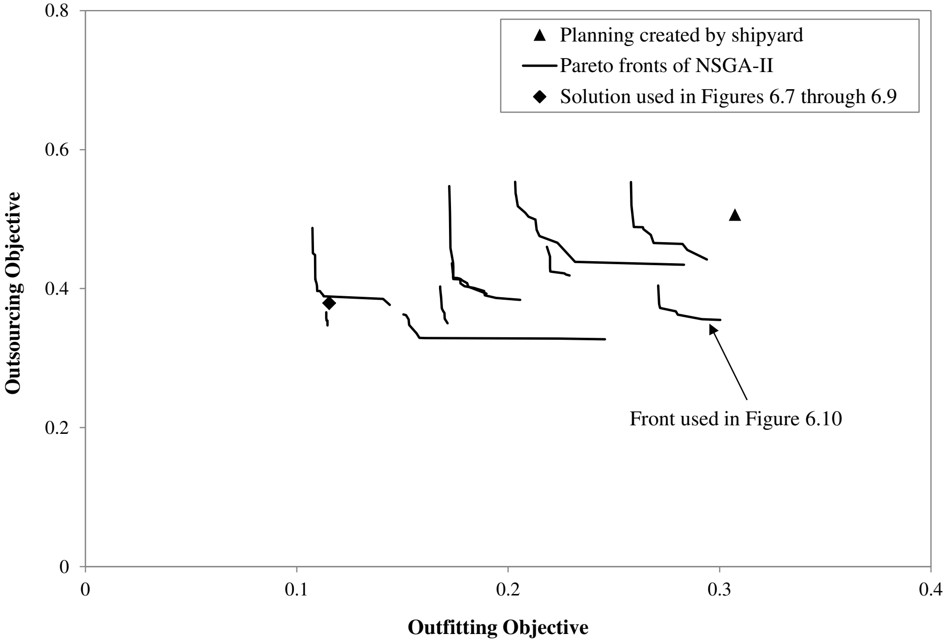
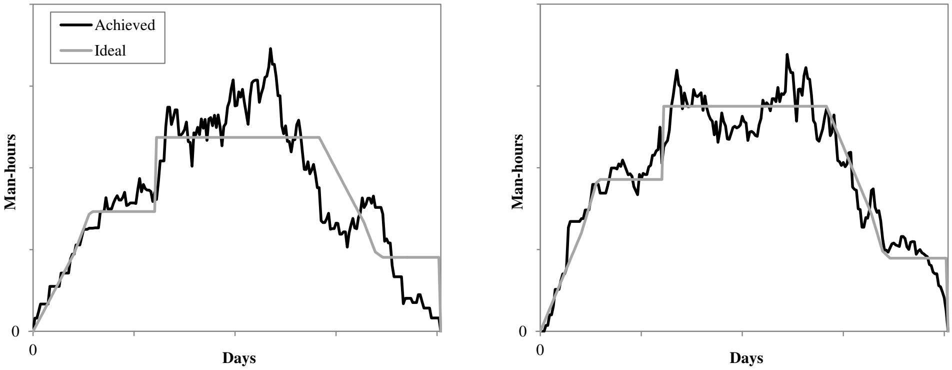


Figure 6.6: Pareto fronts for test case ship, $O_{res} \leq 8200000$



(a) Shipyard planners **(b)** NSGA-II

Figure 6.7: Total required resources (axes equally scaled)

Figure 6.8 examines the outsourcing characteristics of both production schedules. This figure indicates that the selected solution created by the developed methodology performed significantly more section building and block building work on-site. Even though the selected solution performed a greater percentage of the total workload on-site, this plan outsourced 100% of the block building tasks. The actual plan outsourced 78% of these tasks. The selected solution outsourced all of these tasks since building blocks on-site significantly hinders the section building process due to the high floor space requirements of block building. This type of trade-off can only been seen and analyzed by using a combined model of the section building and erection process since the influence of both of these processes on each other are dynamically calculated.

Figure 6.9 compares the time available for slipway outfitting for densely outfitted areas of the test case ship between the actual plan and the selected solution. This figure indicates that the selected solution distributed the slipway outfitting time much more evenly, with a majority of the densely outfitted area having between 20 and 40 days. In contrast, the majority of the area for the erection schedule created by the shipyard planners had either no days for slipway outfitting or more than 50. This reflects the fact that the actual plan was created with very little consideration of the slipway outfitting process beyond the requirement that large equipment can be placed inside the ship.

Figure 6.10 presents a set of parallel coordinate plots for one trial, indicated in Figures 6.4 through 6.6. These plots compare the scaled values of the objectives for each solution in the Pareto surface, allowing the trade-offs between the objectives to be visualized. Figures 6.10(a) through 6.10(c) present the same set of data in three different arrangements. Each plot focuses on one of the objectives by placing that objective in the center and highlighting the top 10% of solutions with respect to the selected objective. For example, the left halves of Figures 6.10(a) and 6.10(b) both describe the relationship between the Resource Objective and the Outfitting Objective for the solutions in the Pareto front of the selected trial. However, Figure 6.10(a) focuses on the Resource Objective by highlighting the top solutions relative to this objective and placing the Resource Objective axis in the center of the plot.

Figure 6.10(a) indicates that a trade-off exists between the Resource Objective and the other two objectives. This trade-off is especially strong for the Outsourcing Objective as the best solutions for the Resource Objective were some of the worst solutions with respect of the Outsourcing Objective. Figures 6.10(b) and 6.10(c) indicate that it was possible to find solutions with high performance with respect to both the Outsourcing and Outfitting Objective. No direct trade-off exists between these objectives because they are measured from different processes, the Outfitting Objective from erection and the Outsourcing Objective from section building. Overall, Figure 6.10 indicates that a shipyard would need to sacrifice some performance relative to resource leveling to improve their slipway outfitting and outsourcing. The parallel coordinate plots were also examined for several other trials and similar trends were observed.

6.7 Validation

The Combined Erection and Section Building Planning Method was validated in the same way as the Erection Planning Method and Section Building Planning Method (see Sections 4.7 and 5.7). No separate validation sessions were conducted for the validation of the Combined Erection and Section Building Planning Method since this method does not introduce any new types of constraints. Instead, the existing constraints of the erection and section building processes were used to model block building. Furthermore, no additional input data was required. This also implies that the conclusions regarding validation drawn in Sections 4.7 and 5.7 can also be applied to the Combined Erection and Section Building Planning Method.

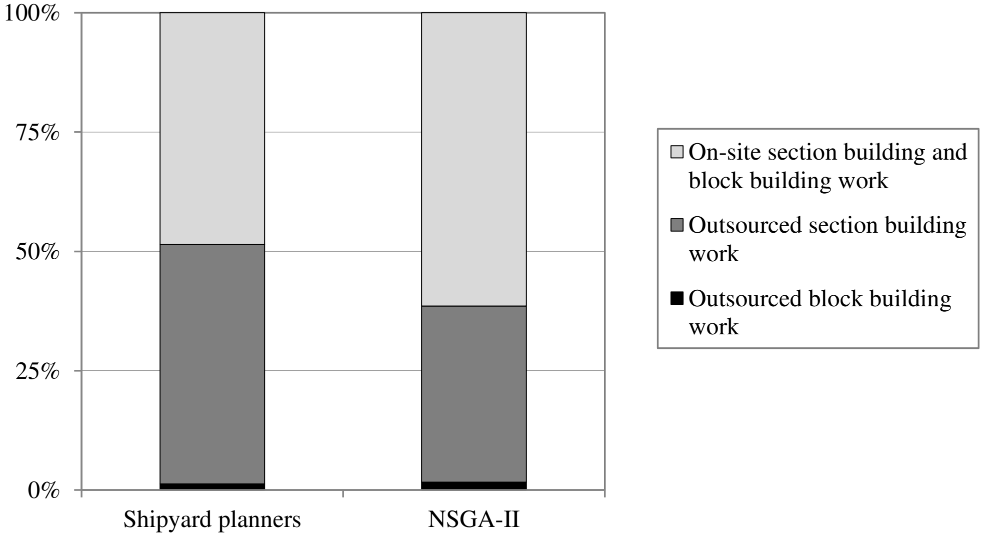


Figure 6.8: Percent of outsourced workload

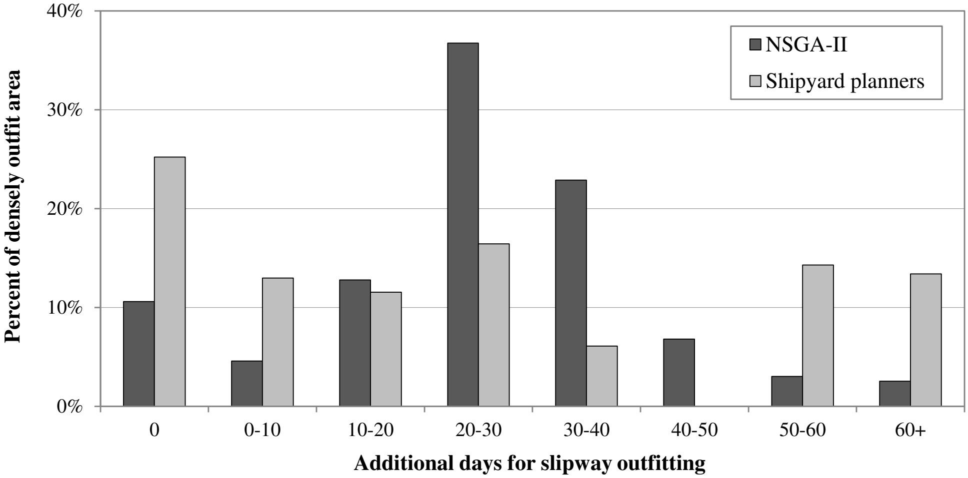


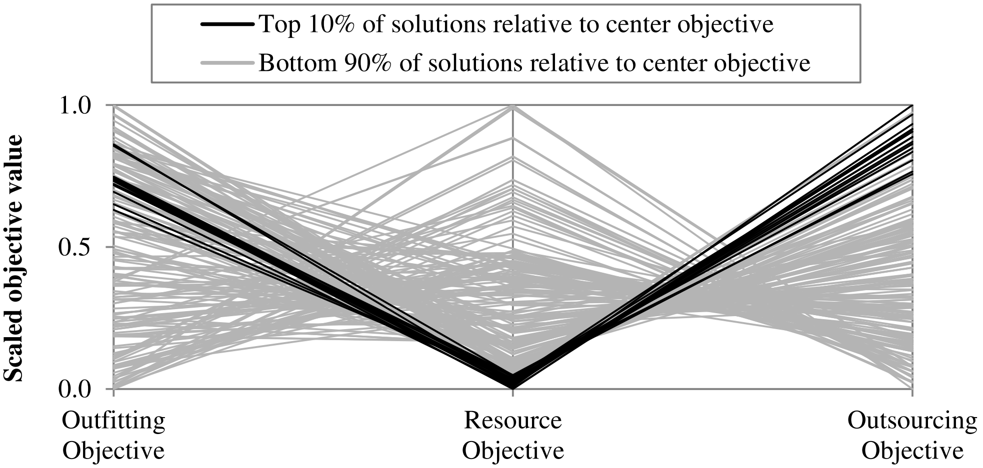
Figure 6.9: Time available for slipway outfitting

6.8 Implementation

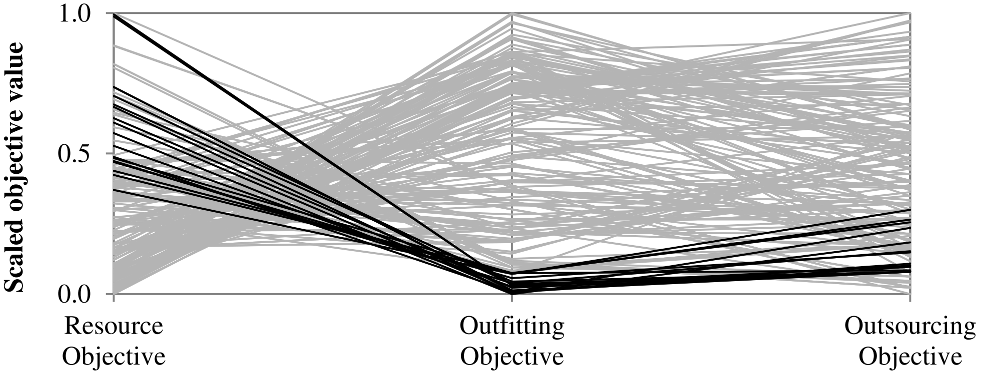
Shipyard planners could use the methodology for automatically generating a Section Building and Erection Plan developed in this chapter as a starting point for creating the initial plan of a new shipbuilding project. This could be done similarly to the implementation of the method developed for automatically generating an Erection Plan (described in Section 4.8). Furthermore, shipyards could use this method as a decision making tool for selecting production strategies or evaluating potential shipyard improvement ideas. For example, an analysis could be performed for a ship to determine the optimal block building strategy. Such an analysis is performed in Section 8.1 for the test case ship. Selecting the optimized block building strategy requires analyzing the trade-off between easing the workload on the slipway against additional space restrictions in the section building hall. Individual models of each of these processes cannot fully calculate this trade-off since both processes are not considered simultaneously in an integrated manner.

6.9 Conclusion

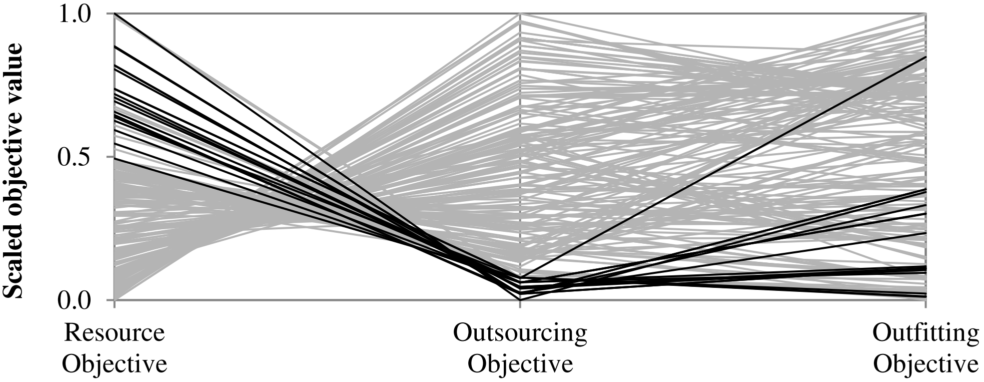
The Combined Erection and Section Building Planning Method module of the Integrated Shipbuilding Planning Method is developed in this chapter. This chapter first defines a mathematical model for the combined erection and section building process of European shipyards building complex ships. A methodology, based on the NSGA-II, is also developed for solving this mathematical model. A test case of a pipelaying ship recently built at a Dutch shipyard is used to show the feasibility of both the mathematical model and solution technique. It was possible to consistently generate production schedules for the test case ship that were superior to the plan used by the shipyard with respect to all three considered objectives. These objectives evaluated the schedules based on resource leveling, the time available for slipway out-



(a) Focus on Resource Objective



(b) Focus on Outfitting Objective



(c) Focus on Outsourcing Objective

Figure 6.10: Parallel coordinate plots for one trial

fitting, and the outsourced workload. The developed methodology required negligible computation time.

The planning method presented in this chapter is not designed to replace existing shipyard planners. Instead, this method should enhance the decision making abilities of these planners by providing them with a variety of high-quality production schedules. Ideally, the planners would find one of the proposed solutions to be suitable as a starting point for drafting the initial Erection and Section Building Plan of a new project. The trade-off between the three considered objectives is still left to the discretion of the planners. The developed methodology could also be used by a shipyard to make strategic decisions, such as evaluating and optimizing their block building strategies. Such an analysis is presented in Section 8.1. The next chapter will develop the final module of the Integrated Shipbuilding Planning Method, the Detailed Outfitting Planning Method.

Chapter 7

Detailed Outfitting Planning Method*

The Detailed Outfitting Planning Method is developed in this chapter. This method is a module of the Integrated Shipbuilding Planning Method proposed in Chapter 3. The Detailed Outfitting Planning Method automatically determines the optimal start time of the outfitting tasks required to build a ship, including the installation of piping, HVAC ducts, cable trays, and equipment.

To generate a detailed Outfitting Plan, scheduling techniques developed by the operations research community can be applied to a mathematical model of the outfitting process, refereed to as the ship outfitting scheduling problem (SOSP) in this chapter. Fundamentally, the SOSP is a variation of the resource availability cost problem (RACP), also referred to as the resource investment problem (RIP) in some literature. The RACP seeks to schedule a set of tasks within a strict project deadline while minimizing the total number of resources required. The Erection and Section Building Plan indicate the allowable time windows and deadlines for outfitting. Furthermore, the monetary penalties incurred from late ship delivery are generally very high since owners plan charters for a ship based on its delivery date (Schank et al., 2005). Moreover, no hard limitations exist on the number of outfitting teams any subcontractor can assign to a given project at a given time.

To adequately model the SOSP, the traditional RACP formulation must be expanded. First, time windows are added to specify the intervals during which outfitting can be performed. The allowable time windows for outfitting each section (pre-outfitting, slipway outfitting, and quay outfitting) come from the Erection and Section Building Plan of a ship. Because the required time to outfit a component is a function of the outfitting stage during which the component is installed, the RACP must be expanded to cover phase dependent task execution times. Sequence dependent setup times are also included to account for the fact that additional time is required when mounting teams move between work sites. Lastly, the outfitting process of shipbuilding is partly governed by complex precedence relations that cannot be modeled by the simple start-finish precedence relations traditionally included in the RACP. All

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*This chapter is partially based on Rose and Coenen (2015a,b,c, 2016c); Rose et al. (2016).

these elements are incorporated in the mathematical model developed for the SOSP.

This chapter first reviews the relevant outfitting scheduling literature. Next, a qualitative description and mathematical model of the outfitting process are presented, defining the constraints and objectives that govern the process. The development of the methodology used to solve the mathematical model is then described in detail. The quality and effectiveness of this methodology were evaluated using a test case of a recently delivered pipelaying ship. The test case is also used to generate feedback to the Erection and Section Building Planning Methods developed in Chapters 4 and 5. The potential implementation of the Detailed Outfitting Planning Method is discussed at the conclusion of this chapter.

7.1 Literature Review

An extensive literature review of the ship outfitting planning process was performed by Wei (2012), who concluded that shipbuilding literature only covered the topic in a cursory manner. Wei qualitatively described some of the constraints governing the outfitting process and developed a method for automatically generating an assembly sequence of outfitting components within a single section. A summary of her work is presented in Wei and Nienhuis (2012). Rose and Coenen (2015b) expanded the work of Wei by developing and comparing several meta-heurstics to automatically generate an outfitting schedule for a single section. Several other attempts have also been made to define the constraints of this process. Graves and McGinnis (1982) formally modeled the outfitting process of U.S. shipyards building naval ships as a generalization of the resource constrained project scheduling problem (RCPSP). These authors do not attempt to solve their model and only suggest that a heuristic procedure would be required due to the model's complexity. The different constraints governing the outfitting process of modern shipyards building complex ships are examined in varying levels of detail by König et al. (2007), Wei et al. (2010), Wei (2012), and Carrasquilla (2013).

The RACP was first introduced by Möhring (1984) who also proved that it was NP-complete. This means that it is not possible to develop an algorithm to solve the general case of this problem in polynomial time. The RACP is the dual problem of the RCPSP, which seeks to minimize a project deadline under resource constraints as opposed to minimizing the required number of resources under time constraints (Hartmann and Briskorn, 2010). Overall, the available scheduling literature for the RACP is extremely scarce, contrasting with the extensively studied RCPSP. Möhring (1984) and Demeulemeester (1995) prove that the RACP can be solved using a set of RCPSPs where the number of available resources are increased until a schedule is found that meets required project deadline. Drexl and Kimms (2001) used Lagrangian relaxation and a column generation technique to determine lower and upper bounds of the classical RACP formulation.

Several variations of the RACP have also been studied. Neumann and Zimmermann (1999) examined the RACP with time windows and three different objective functions, Hsu and Kim (2005) addressed the multi-mode variation of the problem, and Yamashita et al. (2007) analyzed the RACP under uncertain task execution times. Other formulation variations required for the SOSP, such as sequence dependent setup times, have been addressed for the RCPSP (see Hartmann and Briskorn (2010) for a comprehensive literature review). Due to their relatively similar problem structures, extensions to the RCPSP formation can often be applied to the RACP. Although most of the extensions required to model the SOSP have been addressed individually in literature, no sufficient formulation has been found to fully model the SOSP.

Complex precedence constraints have only been covered in a cursory manner by all scheduling literature, which works almost exclusively with simple precedence relations known a priori. Möhring et al. (2004) defined AND/OR precedence constraints for parallel machine scheduling, which state that at least one of a set of activities must be completed to start another. Kuster and Jannach (2006) examined exclusion type precedence constraints for a RCPSP formulation of the airport turnaround handling process. These constraints specify when two tasks cannot be executed simultaneously. Overall, the available scheduling literature on complex precedence constraints is inadequate to fully model the SOSP.

7.2 Problem Description

The outfitting tasks included in this analysis are those completed by small mounting teams, often employed by specialized subcontractors. Typical outfitting tasks include the installation of pipes, cable trays, HVAC ducts, foundations, and equipment. The vast majority of component installation tasks are of this type, except for the installation of large equipment. Large equipment, such as the main engines and generator sets, is often installed by larger teams that are employed by the equipment suppliers. Each outfitting team can only work on the installation of components belonging to their discipline. The objective of the outfitting process is to minimize the number of outfitting teams required for a shipbuilding project. The assumption is made that once an outfitting team is hired it will continue to work for the duration of the shipbuilding project to stress the importance of having a level workforce (Meijer et al., 2009).

A complex ship can be composed of up to 50,000 components (Wei et al., 2010) that are each individually considered. Every component has a deadline, which is either dictated by the painting date of the room in which the component is installed, the testing date of the system to which the component belongs, or the latest point during which the component can be installed due to size restrictions. The Deadline Constraints ensure that all components are installed prior to their deadlines.

Components can only be installed during certain outfitting stages (or time windows), which correspond to the shipbuilding stages of the sections and compartments to which the components belong. The Time Window Constraints guarantee that each component is installed during one of these time windows. The definition of these time windows comes from the Erection and Section Building Plan of a ship. Figure 7.1 describes the shipbuilding stages relevant to the outfitting of a complex ship. The first two stages, assembly and pre-outfitting, are performed in the section assembly area. During the assembly stage, the panels of the section are welded together. The pre-outfitting stage, which typically overlaps slightly with the assembly stage, allows for the installation of some components while the section is still very easy to access. Next, the section is transported to the paint hall. The section may be temporarily placed in a storage location before or after this stage. The section is then erected on the slipway and is available for slipway outfitting while the rest of the sections are being erected. Once all of the sections are erected, the ship is launched and then moored at the quay until it is ready for sea trials.

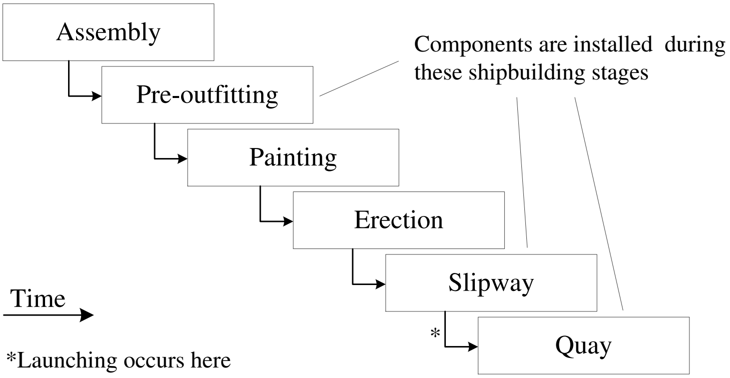


Figure 7.1: Shipbuilding stages of complex ship construction

The mounting time of a component is dependent on the outfitting stage during which the component is installed. Schank et al. (2005) describe the reason for the additional installation time associated with the later mounting stages and propose a series of factors to estimate this time increase. The contributing factors are the additional travel time of mounting teams, components, and tools associated with slipway and quay outfitting as well as the increasingly cramped working conditions. The setup time required prior to installing a component is a function of the previous work location of the mounting team. When a mounting team changes work sites, additional time is not only required for the movement of personnel and tools, but also for the mounting team to familiarize itself with the new environments (reading drawings, finding power supplies and exits, etc.) (Wei, 2012).

The remaining constraints governing the outfitting process relate to the assembly sequence of components. The first of these are the Collision Free Installation Path Constraints. Figure 7.2 illustrates the motivation behind these constraints. The mounting sequence of the components included in this figure ensures that workers are able to place components without needing to remove previously mounted ones. Furthermore, such a sequence guarantees sufficient access and an open working space for the mounting teams.

Wei (2012) developed a method for defining the Collision Free Installation Path Constraints between components in a section by looking for one-dimensional interferences between components in the vertical direction. However, as noted by Wei, this method fails to take into account the steel structure of a section and the 3D nature of the outfitting process. Wei recommended an improvement to her own method which is implemented here. First, each component is assigned to whichever boundary is closest to that component. Figure 7.3 presents an example of how a group of components in a section are assigned to the boundary closest to them.

Next, the 1D interferences between each of the components associated to a boundary are calculated in the normal direction of that boundary. When an interference exists between two components, the component closer to the boundary must be mounted prior to the one further away. Figure 7.4 contains an example of the Collisions

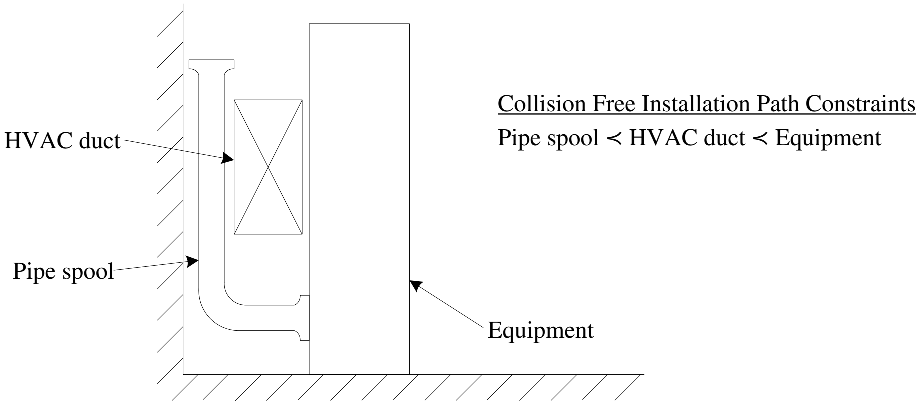


Figure 7.2: Motivation for Collision Free Installation Path Constraints

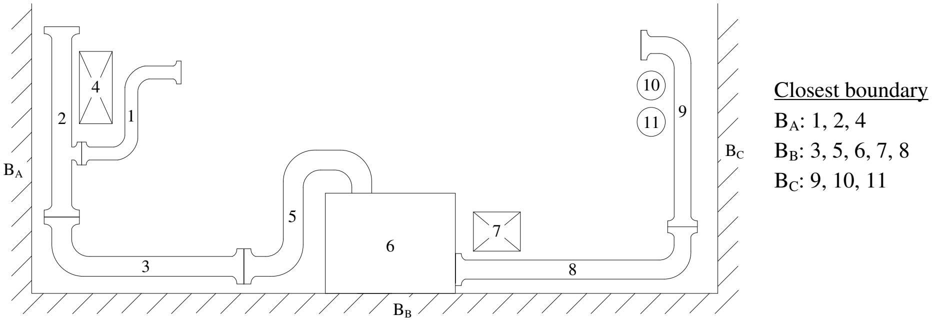
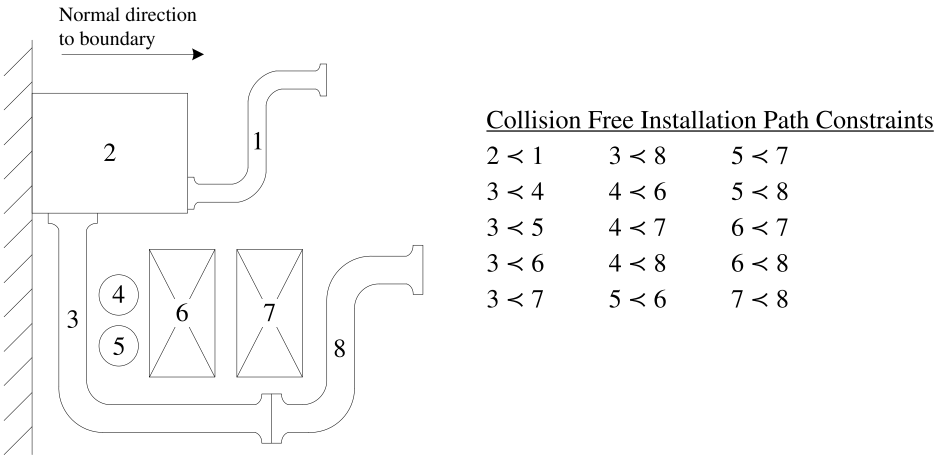


Figure 7.3: Assignment of components to closest boundary

Free Installation Path Constraints that exist for a group of components associated with the same boundary.

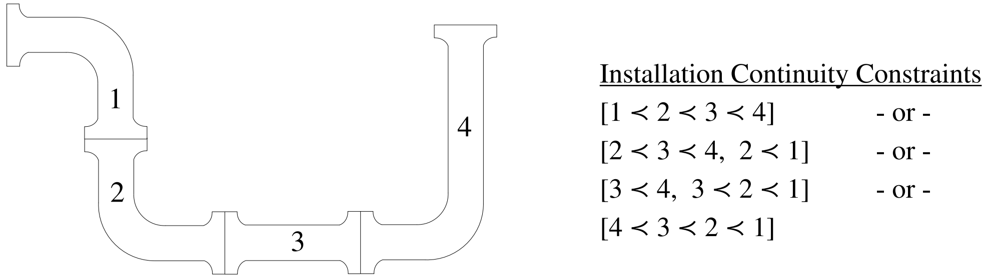
The next set of assembly sequence constraints are the Installation Continuity Constraints. Wei (2012) shows it is bad practice to mount a pipe spool (or HVAC duct) between two already mounted ones due to the additional alignment work required when trying to match both ends of the pipe simultaneously. Furthermore, assembly teams usually prefer to start mounting a pipe from a penetration piece, also for alignment reasons. Therefore, if a pipe has at least one penetrating pipe spool, one of those components should be mounted first. If a pipe has no penetrations, any spool of that pipe can be mounted first. Figures 7.5 through 7.7 describe the Installation Continuity Constraints for pipes with zero, one, and two penetration pieces respectively. Note that these constraints become even more complex for pipes with branches, but the underlying logic is identical. Due to the complex nature of the pipe routing in ship sections, a set of infeasible constraints could occur when combining the Collision Free Installation Path and Installation Continuity Constraints. In this case, the Installation Continuity Constraints should be relaxed as the additional alignment work associated with violating these constraints is less than the work required for removing and remounting an already mounted component (especially if that component



Collision Free Installation Path Constraints

2 ≺ 1	3 ≺ 8	5 ≺ 7
3 ≺ 4	4 ≺ 6	5 ≺ 8
3 ≺ 5	4 ≺ 7	6 ≺ 7
3 ≺ 6	4 ≺ 8	6 ≺ 8
3 ≺ 7	5 ≺ 6	7 ≺ 8

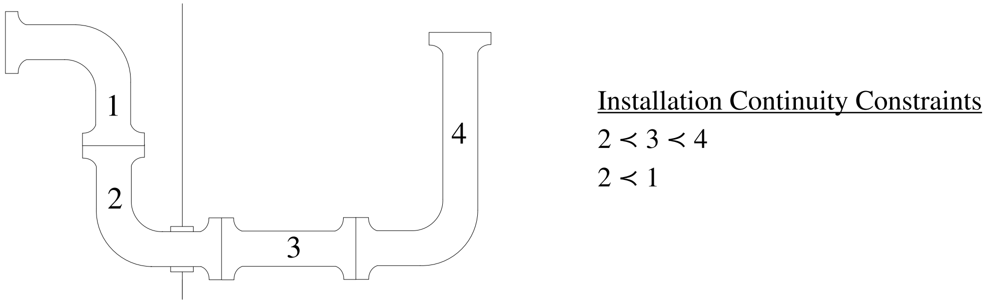
Figure 7.4: Collision Free Installation Path Constraints between components



Installation Continuity Constraints

[1 ≺ 2 ≺ 3 ≺ 4] - or -
[2 ≺ 3 ≺ 4, 2 ≺ 1] - or -
[3 ≺ 4, 3 ≺ 2 ≺ 1] - or -
[4 ≺ 3 ≺ 2 ≺ 1]

Figure 7.5: Installation Continuity Constraints for pipe with no penetrations



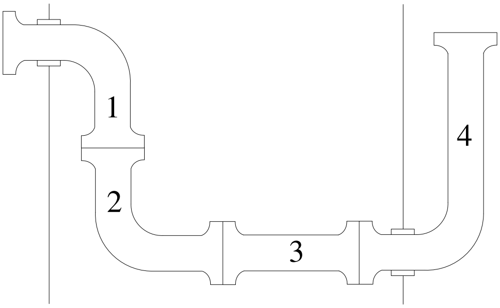
Installation Continuity Constraints

2 ≺ 3 ≺ 4
2 ≺ 1

Figure 7.6: Installation Continuity Constraints for pipe with one penetration

requires an assembly team of a different discipline).

The last set of assembly sequence constraints (Minimum Safe Working Distance Constraints) enforce a safe working distance between mounting teams. A detailed rationale behind these constraints is found in Wei (2012). Components separated by less than some minimum safe working distance should not be installed simultaneously



Installation Continuity Constraints

$[1 \prec 2 \prec 3 \prec 4]$ - or -

$[4 \prec 3 \prec 2 \prec 1]$

Figure 7.7: Installation Continuity Constraints for pipe with two penetrations

to ensure that mounting teams do not encroach in each other's working areas. This results in a complex set of precedence relations between those components, where it is irrelevant which component is mounted first, yet the installation of one of the components must precede the other. The Minimum Safe Working Distance Constraints are represented as exclusion type precedence relations. An exclusion type precedence relation between two tasks ensures these two tasks cannot be executed at the same time.

7.3 Mathematical Model

To define the ship outfitting scheduling problem, the classical RACP formulation was adapted to include phase dependent task execution times, sequence dependent setup times, time windows, complex precedence constraints, and individual task deadlines. The number of resources required per task was also limited to one since multiple outfitting teams do not work on the same activity. The mathematical model developed in this section is based on the qualitative description of the outfitting process presented in the previous section. The following notation is used:

i	index used for tasks
j	index used for tasks
k	index used for outfitting disciplines
n	index used for work locations
m	index used for work locations
u	index used for outfitting stages
v	index used for component groups
l	index used for starting tasks in a component group
t	index used for time
N	set of installation tasks
R	set of outfitting disciplines
S	set of possible outfitting stages
G	set of component groups
x_i	start time of task i
d_i	duration of task i
b_i	base duration of task i

f_i	base time multiplication factor of task i
z_i	deadline of task i
w_i	work location of task i
y_i	setup time of task i
ξ_u	base duration multiplication factor associated with outfitting stage u
Θ_v	set of tasks in component group v which involve mounting a penetrating component
Φ_v	set of tasks in component group v that could potentially be the starting task
Ω_v	set of all tasks required to install component group v
a_k	total number of mounting teams required for discipline k
$\beta_{n,m}$	time required for mounting team to relocate from work location n to work location m
$\Psi_{i,u}$	set of all possible start times during which task i can be completed during outfitting stage u
η_i	task performed immediately prior to task i using the same mounting team, where $\eta_i = \emptyset$ if team was previously idle
$E_{t,k}$	set of all tasks requiring a resource of discipline k executed during time t
C_k	function for calculating the cost of hiring a specific number of mounting teams for discipline k
P	set of Collision Free Installation Path Constraints, where $(i, j) \in P$ if such a constraint exists between task i and task j
Q	set of Minimum Safe Working Distance Constraints, where $(i, j) \in Q$ if such a constraint exists between task i and task j
$H_{l,v}$	set of finish-start precedence relations required to satisfy Installation Continuity Constraints for component group v when starting with task l, where $(i, j) \in H_{l,v}$ if such a constraint exists between task i and task j
T	set of all considered time steps
O_{cost}	objective

The objective function of the mathematical model is shown by Equation 7.1. This function calculates the total cost required to hire the mounting teams, which should be minimized.

$$O_{cost} = \sum_{k \in R} C_k(a_k) \tag{7.1}$$

The number of mounting teams required for each discipline is calculated by Equation 7.2, which determines the maximum number of mounting teams used at any point in time over the duration of the outfitting process.

$$\sum_{i \in E_{t,k}} i \le a_k \qquad \forall k \in R, \forall t \in T \tag{7.2}$$

The duration of each installation task depends on the outfitting stage during which that task is completed. Equation 7.3 calculates the duration of each task, a function of that task's base duration, base time multiplication factor, and setup time.

$$d_i = f_i \times b_i + y_i \qquad \forall i \in N \tag{7.3}$$

The base duration represents the mounting time under ideal conditions, and the characteristics of the shipyard dictate the base duration multiplication factor associated with each outfitting stage. The base time multiplication factor for each installation task is a function of the outfitting stage during which the component was installed and is determined using Equation 7.4.

$$b_i = \xi_u \qquad \forall i \in N, \forall u \in S, x_i \in \Psi_{i,u} \tag{7.4}$$

The required setup time of each installation task is a function of the previous work location of the mounting team assigned to perform that task. This setup time accounts for the time required for the mounting team to travel between the different work locations and also for the time required for the team to orient themselves to their new surroundings. Equation 7.5 calculates the required setup time for each task.

$$y_i = \begin{cases} 0 & \text{if } n = m \\ 0 & \text{if } m = \emptyset \\ \beta_{n,m} & \text{otherwise} \end{cases} \qquad n = w_i, m = w_{\eta_i}, \forall i \in N \tag{7.5}$$

Equation 7.6 requires each task to be executed during one of its allowable outfitting stages, enforcing the Time Window Constraints.

$$x_i \in \Psi_{i,u} \qquad \forall i \in N, u \in S \tag{7.6}$$

Equation 7.7 enforces the Deadline Constraints.

$$x_i + d_i \leq z_i \qquad \forall i \in N \tag{7.7}$$

Equation 7.8 ensures that the Collision Free Installation Path Constraints are meet.

$$x_i + d_i \leq x_j \qquad \forall (i,j) \in P \tag{7.8}$$

Equation 7.9 enforces the Minimum Safe Working Distance Constraints.

$$x_i + d_i \leq x_j \quad \text{or} \quad x_j + d_j \leq x_i \qquad \forall (i,j) \in Q \tag{7.9}$$

Sets of complex precedence constraints are defined to enforce the Installation Continuity Constraints. One set of these constraints is defined per component group, where a component group is either a pipe line or HVAC duct line. Equation 7.10 ensures that the outfitting schedule adheres to the Installation Continuity Constraints.

$$x_i + d_i \leq x_j \qquad \forall (i,j) \in H_{l,v}, \forall v \in G, l \in \Phi_v \tag{7.10}$$

The set of possible starting components for each component group is calculated using Equation 7.11.

$$\Phi_v = \begin{cases} \Theta_v & \text{if } \Theta_v \neq \emptyset \\ \Omega_v & \text{otherwise} \end{cases} \qquad \forall v \in G \tag{7.11}$$

7.4 Methodology

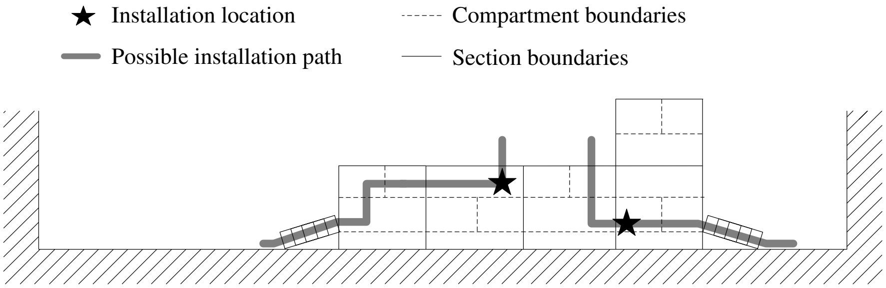
This section describes the methodology developed to solve the mathematical model presented in the previous section. First, a method was developed for automatically determining the latest point in time a component can be transported to a compartment. This method is required for calculating the deadline of each outfitting task. Next, a brief investigation was conducted into the feasibility of using meta-heuristics. This investigation concluded that these optimization techniques are too computationally intensive for this application. The approach used, a list scheduling heuristic, is then described. The methodology section concludes with a description of the method used to determine the relative priorities of outfitting tasks. These priorities are required input for the list scheduling heuristic.

7.4.1 Determining the Latest Possible Component Installation Times

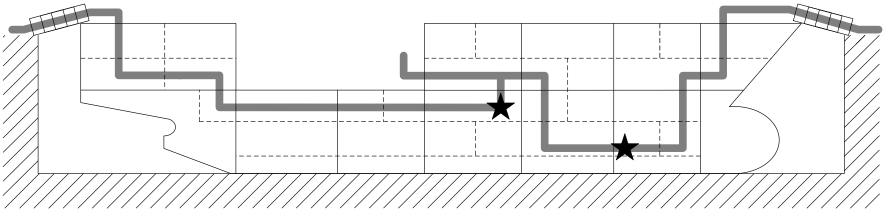
Knowing the latest possible point in time during which a component can be installed is required to automatically generate an Outfitting Plan because the deadline of each task is dependent on this time. Rose and Coenen (2015a) developed a method of automatically determining this point in time. This section presents a summary of their methodology. A more detailed description of the methodology as well as a test case showing the feasibility of the approach is found in the paper.

The latest possible installation time of an outfitting component is a function of the component's size and the erection process. Components of any size can be installed in a compartment on the slipway while vertical crane access still exists to that compartment. However, once the sections composing the ceiling of a compartment have been erected, transporting a component to the compartment is no longer as simple as dropping the equipment into the compartment using a crane. Instead, the component must be placed in an adjacent compartment that is still vertically accessible and then transported to the compartment using the routes available internally within the ship. As more and more sections are erected around a compartment, the internal transportation options become increasingly restricted until only relatively small components can be transported to a compartment. Figure 7.8 illustrates some possible transportation paths for several components.

To determine the latest point in time a component can be installed, a set of curves is constructed for each of a ship's compartments that indicate the largest possible object transportable to that compartment during each stage of the erection process. These curves are used to quickly determine the latest installation time of any component based on its size and location.



(a) Early in the erection process



(b) Late in the erection process

Figure 7.8: Possible installation paths for two components

Problem Description

The internal transportation of components within a ship is modeled as a bi-objective bottleneck shortest path problem, where the nodes represent a ship's compartments and the edges represent the openings connecting the compartments in two dimensions, width and height. The network is expanded each time an additional section is erected. The bi-objective bottleneck shortest path problem, first mentioned in literature by Hansen (1980), is a variant of the commonly studied shortest path problem. A rigorous mathematical definition of this problem as well as a proof of its complexity is found in Hansen (1980). The adaptation of this definition for equipment installation transportation routes in shipbuilding is described in Rose and Coenen (2015a).

Solving the bi-objective bottleneck shortest path problem results in a Pareto front specifying the 2D size limits for a given state of the erection process. Additional vertices and arcs are added to the graph each time a new section is erected on the slipway. Therefore, a new Pareto front must be calculated. Expanding the graph can only further restrict access to a compartment. This means that the Pareto front can only decrease in magnitude over time. However, erecting additional sections only affects the shape of the Pareto front if the newly erected section interferes with one of the previously optimal paths. For example, it is unlikely that erecting a bulbous bow section will affect the size of equipment which can be transport into a stern thruster compartment. Figure 7.9 illustrates an example of a set of curves which indicate the maximum component sizes that can be transported into a section as a function of time.

Pareto fronts describing the access limitations to a compartment only need to be

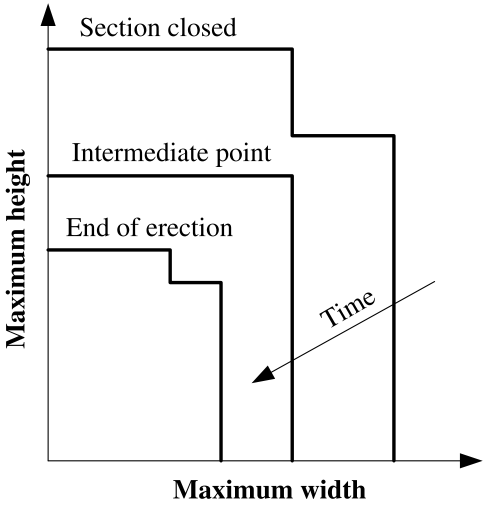


Figure 7.9: Size restrictions as a function of time for an example compartment

generated for compartments containing large outfitting objects. If a compartment only contains components which can be easily transported through standard ship openings, the deadline of installing those components are determined by the outfitting plan. In general, this means that the previously described analysis must only be performed for technical spaces containing large equipment (such as generator sets, heat exchangers, purifiers, switchboards, etc.).

Solution Approach

When defining the bi-objective bottleneck shortest path problem, Hansen (1980) also proposed an algorithm for finding the solution. Hansen's algorithm creates the Pareto front of solutions by solving a set of single objective bottleneck shortest path problems, alternating between the two objectives. Hansen suggests using a polynomial time algorithm, such as Dijkstra's algorithm, to solve the single objective cases. This approach is referred to as Hansen's (original) algorithm in this dissertation.

One disadvantage of using Dijksta's algorithm for solving bottleneck type problems is that the algorithm is not specifically designed for the bottleneck problem structure. Kaibel and Peinhardt (2006) show that a threshold type approach requires less computational time to solve single objective bottleneck shortest path problems. Hansen's algorithm can be modified to use a threshold algorithm, referred to as Hansen's (revised) algorithm in this dissertation. The concept of using a threshold type approach can also be expanded to directly solve the bi-objective bottleneck shortest path problem. Rose and Coenen (2015a) develop this type of solution method, referred to as the 2D threshold algorithm.

Each of the previously described algorithms are only capable of solving the bi-objective bottleneck shortest path problem for a single compartment. If the size restrictions are calculated for several compartments, then the algorithms need to be run several times. Martins (1984) proposes an algorithm that solves the bi-objective bottleneck shortest path problem for all vertices in a network at once. Martins' algorithm is the multi-objective extension of Dijkstra's algorithm. Because Martins' algorithm inherently solves the entire network, only a marginal increase of computational effort is required for the additional compartments.

Rose and Coenen (2015a) perform a test case of a complex ship to compare the performance of these four algorithms. For the case of a single compartment, the computational time of each algorithm was highly dependent on the specific arrangements of compartment network. Although the computational time generally increased as the network size increased, no definitive correlations could be deduced which link the number of vertices and edges to the required computational time. However, Hansen's (revised) algorithm had the lowest computational requirements. Therefore, this algorithm provides the best performance for the case of a single compartment.

However, the computational effort of Martins' algorithm only marginally increased with the number of compartments that are examined while the computational times of the other three algorithms increased at a polynomial rate. This type of result was expected based on each algorithm's structure. Martins' algorithm required the least computational effort for the test case ship when more than four different compartments were examined. Because modern complex ships have significantly more than four technical spaces with large equipment, Martins' algorithm provides the best performance when creating the curves used to determine the latest possible component installation times.

7.4.2 Meta-heuristics

The mathematical model for ship outfitting scheduling described in Section 7.3 is computationally difficult to solve for several reasons. First, scheduling is an inherently complex problem. When Möhring (1984) first formally defined the RACP, he also proved that the problem was NP-complete. This means that it is not possible to find a general algorithm for solving the RACP in polynomial time. Furthermore, the computational complexity is only increased compared to the classical RACP through the addition of sequence dependent setup times, complex precedence constraints, non-deterministic task times, and allowable time windows.

Secondly, ship outfitting scheduling is an extremely large problem. A complex ship can have upwards of 50,000 different components, each with an individually scheduled installation task (Wei et al., 2010). Sample scheduling problems found in operations research literature generally consider cases ranging between 20 and 2,000 tasks. Due to the exponential nature of the computational requirements relative to problem size required for scheduling problems and the extremely large number of outfitting components in a ship, exact solution techniques are not a viable option for the planning of ship outfitting.

Instead, heuristic solution techniques offer a feasible alternative to generating ship outfitting schedules. These techniques attempt to find high-quality solutions, although not necessarily mathematically optimal ones, in reasonable computational times. This type of approach is especially suited for ship outfitting scheduling since shipyards do not actually need the mathematically optimal outfitting plan. Instead, a high-quality schedule is generally sufficient.

Literature shows that meta-heuristics are one of the most effective types of heuristics for solving scheduling problems in terms of solution quality. Meta-heuristics are high-level, general algorithms applicable to most problem structures. Successful examples of meta-heuristic algorithms applied to production scheduling problems include genetic algorithms (Vilcot and Billaut, 2008; Sakalauskas and Felinskas, 2006), simulated annealing (Varadharajan and Rajendran, 2005; Boctor, 1996), particle swarm optimization (Zhang et al., 2005; Linyi and Yan, 2007), and ant colony optimization (Berrichi et al., 2010). Chapters 4 and 5 also show that meta-heuristics can be effectively used to automatically create production schedules for the steel-related portion of the shipbuilding process of complex ships. However, the number of tasks which must be considered to create a detailed Outfitting Plan is significantly larger, increasing the computational requirements. Rose and Coenen (2015b) compare the performance of four different meta-heuristics for automatically creating a detailed Outfitting Plan. This section contains a summary of this paper.

It should be noted that the problem addressed by Rose and Coenen (2015b) is slightly different than the one presented in this chapter. Mainly, this paper only considers the scheduling of outfitting tasks within a single section under fixed resource requirements. This means that the problem size studied is significantly smaller and the interactions between different sections are excluded. Furthermore, the objective used seeks to simultaneously minimize the required outfitting time as well as maximize the ease of outfitting. However, the same type of constraints between outfitting tasks are used. Therefore, this paper gives a good indication about the feasibility of implementing meta-heuristics for automatically creating a detailed Outfitting Plan.

Methodology

The four meta-heuristics tested were genetic algorithms, simulated annealing, genetic simulated annealing, and discrete particle swarm optimization. Genetic simulated annealing is a hybrid meta-heuristic combining genetic algorithms with simulated annealing. Genetic simulated annealing aims to keep the advantages of both methods, mainly the broad search area of genetic algorithms and strong local search ability of simulated annealing. Section 2.3.1 contains a description of these meta-heuristics and provides a literature review of their applicability in production scheduling problems.

The definition of the solution space is very important for meta-heuristics since these algorithms usually do not perform well when the solution space is dominated by infeasible solutions. A methodology similar to that of Grajcar (1999) was used to define the solution space. This method involves designing a custom list scheduling heuristic to convert each chromosome into a schedule. This heuristic incorporates the complex precedent constraints required for outfitting.

In general, the traditional implementations of each of the meta-heuristics were implemented. However, some customization was necessary to apply these meta-heuristics to a discrete scheduling problem. For the genetic algorithm, a specialized discrete crossover operator was required to ensure that each newly created chromosome represented a feasible Outfitting Plan. Because the performance of these operators varies greatly depending on the problem structure, five common discrete crossover operators, proposed by Larranaga et al. (1996), were tested. The discrete implementation of particle swarm optimization developed by Sha and Hsu (2006) was used. For genetic simulated annealing, the work of Wang et al. (2009) was modified to create an algorithm that alternated between the two meta-heuristics each generation. The parameters of each meta-heuristic were tuned to optimize their performance.

Results

The methodology developed for creating an outfitting schedule was tested on three different ship sections, all from the same multi-purpose offshore construction ship. The first section, a superstructure section, contained roughly 200 components. The other two sections, engine room double bottom sections, contained roughly 400 components each.

Simulated annealing had the best results for the smaller of the three sections, and the genetic simulated annealing yielded the lowest objective function values on average for the two larger sections. Furthermore, genetic simulated annealing produced the most consistent results in terms of the objective function for the two larger ship sections, while simulated annealing showed more consistent performance for the smaller section. The performance of the particle swarm optimization was significantly worse than the performance of the other methods.

Of all the methods, the genetic algorithm resulted in the smallest increase in computational time as the problem size increased. Therefore, this method may be most suitable for large problems where computational time is important. However, the genetic algorithm required roughly 15 minutes to generate an Outfitting Plan for the smaller section and 2-3 hours for the larger sections. This indicates that the computational requirements will grow exponentially with the problem size. Because a complex ship can have upwards of 50,000 outfitting components, the meta-heuristics tested had far too high computational requirements to be effectively used to automatically generate a detailed Outfitting Plan for an entire ship.

7.4.3 List Scheduling Heuristic

Section 7.4.2 concludes that meta-heuristics are too computationally intensive for scheduling the outfitting tasks of an entire complex ship simultaneously. Therefore, a custom list scheduling heuristic was developed to solve the SOSP. List scheduling heuristics have been shown to provide solutions to the RCPSP in very fast computational times (Brucker et al., 1999). The approach of solving the RACP by solving the feasibility problem of a set of RCPSP with different resource limitations, presented by Möhring (1984) and Demeulemeester (1995), was implemented. As a result, it was critical to have a solution technique which could solve the RCPSP quickly. This is especially important when solving the case of an entire complex ship. Another advantage of using a list scheduling heuristic is that it is possible to implement the complex precedence constraints of the SOSP without drastically altering the algorithm.

One main drawback of using list scheduling heuristics for scheduling is that these algorithms have been shown to have generally poor solution qualities and inconsistent performance compared to complex heuristics methods and meta-heuristics (Brucker et al., 1999). The severity of this drawback depends on the problem structure. Rose et al. (2016) successfully developed and tested a list scheduling heuristic to create a detailed Outfitting Plan for six sections of a pipelaying ship. Their algorithm was able to match the theoretical lower bound for the examined test case. Part of the reason for this high solution quality stems from the relatively under-constrained nature of outfitting.

Furthermore, the solution quality of list scheduling heuristics is highly dependent on the problem structure and the priority rule used. Rose et al. (2016) tested a combination of five simple priority rules, but found that it was necessary to include an additional iteration in their heuristic which assigned a special priority to some tasks. This was required since some tasks had significantly earlier deadlines than the majority of the tasks. Although one of the simple priority rules was based on a task's deadline, it is difficult to determine which other tasks were affected by this deadline due to the complex nature of the precedence constraints governing ship outfitting. Therefore, a custom method was developed for determining the priorities of outfitting components, presented in Section 7.4.4.

One problem with directly implementing static task priorities is that priorities calculated a priori cannot efficiently minimize setup time. Minimizing setup time was found to be one of the key factors to creating an efficient outfitting plan in Rose et al. (2016). Therefore, an additional dynamic priority layer was added giving preference to installation tasks in the same work area. Adding this layer, however, potentially results in a situation where no mounting teams are free to leave their work area to mount a component somewhere else which is very close to its deadline. A second dynamic priority layer which gave an even higher priority to components very close to their deadline was added to prevent this situation from causing infeasible outfitting schedules.

Figure 7.10 describes the list scheduling heuristic used to solve the mathematical model presented in the previous section. This algorithm iteratively solves a set of scheduling problems with resource restrictions. The number of resources available are increased until an outfitting schedule is found that contains all required tasks. The following additional notation is used:

c	selected task
γ_k	lower bound for a_k
A	set of active precedence relations
B_v	set of precedence relations for component group v which guarantee that starting component is in Φ_v
M	set of tasks that can be scheduled
F	set of tasks currently scheduled
ϵ	amount of time prior to deadline for which unscheduled tasks are considered urgent

The first step of the list scheduling heuristic calculates the lower bound for the number of resources required for each discipline. The lower bound is calculated by removing all precedence constraints between tasks and assuming each task requires no setup time. Step 2 sets the number of resources required to the lower bound. The third step creates an initial set of active precedence constraints. Step 4 initializes the set of scheduled components and time.

Step 5 determines which tasks can be executed at the current time. This is done by making sure a resource of the correct discipline is available, all relevant precedence relations are met, the deadline constraint is satisfied, and the time window constraints

```
Step 1. Determine $\gamma_k \; \forall k \in R$
Step 2. Set $a_k = \gamma_k \; \forall k \in R$
Step 3. Set $A = P \cup B_v \; \forall v \in G$
Step 4. Set $t = 0$ and $F = \emptyset$
Step 5. Determine $M$, where $i \in M$ if the following are satisfied:
        (a) $E_{t,k} < a_k$ for resource $k$ required by task $i$
        (b) $(j,i) \notin A, \forall j \in N$ where $x_j + d_j < t$
        (c) $t + d_i \leq z_i$
        (d) $x_i \in \Psi_{i,u}$ where $u \in S$
Step 6. If $M = \emptyset$ go to step 12
Step 7. Select task $c \in M$ with highest priority, where priority is calculated
        using the following (in order listed, lower is better):
        (a) $min(z_c - t - \epsilon, 0)$
        (b) 0 if $y_c = 0$, 1 otherwise
        (c) Priority assigning a priori
Step 8. Calculate $d_c$, schedule $c$ at $t$, and add $c$ to $F$
Step 9. $\forall (c,j) \; or \; (j,c) \in Q$ add $c \prec j$ to $A$
Step 10. If $c$ is the first component of a component group $v \in G$, remove $B_v$ from
         $A$ and add $H_{c,v}$ to $A$
Step 11. Go to step 5
Step 12. Increase $t$ and go to step 5 if $t < max(z_i, \forall i \in N)$
Step 13. If $F \neq N$, increase $a_k \; \forall k \in R$ required by a task in $N \setminus F$ and go to
         step 3
```

Figure 7.10: Algorithm of list scheduling heuristic

are met. The sixth step checks whether any tasks meet these requirements. Step 7 selects the task to be scheduled out of the set of eligible tasks. First, any components close to their deadline are given preference. Next, components are selected that require no setup time. If no components meet either condition, the component with the highest priority is selected.

Step 8 schedules the selected component at the current time. The set of active precedence relations are updated by the tenth step. Steps 5 through 10 are repeated until no more tasks can be scheduled at the current time. Step 12 increases the time.

If the time is increased beyond the latest component of any task, step 13 checks if all components are scheduled. If not, the number of resources available is increased and steps 3 through 12 are repeated.

7.4.4 Determining Task Priorities

The solution quality of the list scheduling heuristic described in the previous section is highly dependent on the priorities assigned to each task a priori. Rose and Coenen (2015c) developed a method for determining the priorities of outfitting components based on the installation deadlines of each component and the complex network of precedence constraints connecting the components. These priorities are calculated by creating latest finish time distributions using Monte Carlo simulation. This method of obtaining priorities was specifically designed to be used in list scheduling type approaches for scheduling the outfitting tasks of an entire ship. This approach is used in this dissertation to determine the static priorities of each outfitting task. The remainder of this section contains a summary of this approach.

Define Subnetworks

Even though a complex ship can have upwards of 50,000 outfitting components, most of these components are not related by any of the constraints described in Section 7.2. For example, the installation of a cable tray in the bridge has little direct impact on the installation of a double bottom pipe in the engine room. Therefore, the entire complex precedence network of the ship was split into subnetworks.

The first level of subnetwork division was based on a ship's sections. Within a section, additional subnetworks were created based on the Collision Free Installation Path and Installation Continuity Constraints. Two components were assigned to the same subnetwork if they were connected by one of these constraints. Minimum Safe Working Distance Constraints were not included in the subnetwork definition since these constraints do little to restrict the allowable installation times of the components. The purpose of the subnetwork groupings is to examine groups of components that heavily influence each other. Furthermore, if these constraints were to be included in the subnetwork definition, all components of the same section would most likely belong to the same subnetwork.

Determine Feasible Start Components

Due to the complex nature of the Installation Continuity Constraints, it is possible for the components of a subnetwork to be connected by many different precedence networks. The number of different possible precedence networks is a function of the number of Installation Continuity Constraints as well as the number of possible start components for each of these constraints. Due to the exponential nature of the number of different precedence networks, it is not always possible to exhaustively check each precedence network permutation to see if the permutation is feasible. However, it is possible to quickly check the feasibility of certain conditions which in turn eliminates large portions of the infeasible permutations from the set of total permutations.

First, the feasibility of each given starting component is examined in isolation with the Collision Free Installation Path Constraints. This is done by creating a new precedence network composed of the Collision Free Installation Path Constraints in a subnetwork as well as the specific Installation Continuity Constraints associated with a given start component. If this precedence network is infeasible, then any precedence network permutation using the selected starting component will also be infeasible.

To further refine the total number of possible permutations of a subnetwork, two sets of Installation Continuity Constraints are examined simultaneously. To do this, a set of precedence relations is created containing the start-finish precedence relations associated with the Collision Free Installation Path Constraints and the Installation Continuity Constraints associated with the two selected start components. If a start component of one set of Installation Continuity Constraints results in an infeasible precedence network when combined with every start component of the other Installation Continuity Constraint, then that selected start component is infeasible.

Calculate Latest Finish Time Distribution

The earliest latest finish time (LFT) was selected as the basis of outfitting priority due to its prevalence in literature, low computational requirements, and potential to provide tangible feedback to shipyard planners. However, the LFT of a component is dependent on which Installation Continuity and Minimum Safe Working Distance Constraints are implemented. Because these constraints are complex, the effect of these constraints on the LFT of the components in a section cannot be determined a priori. Therefore, Monte Carlo simulation was used to construct LFT distributions.

For each iteration of the Monte Carlo simulation, a random start component was selected for each Installation Continuity Constraint. A precedence network was constructed using the start-finish precedence relations of the Collision Free Installation Path Constraints combined with those associated with the selected start components. The LFT was calculated using a backwards list scheduling heuristic that dynamically implements the Minimum Safe Working Distance Constraints. The objective of this algorithm is to schedule each component as late as possible. Using this approach, the LFT of each component is calculated for a randomly selected set of constraints. This process was iterated to determine the LFT distribution for each component.

The installation priority of each component was taken to be the point in time that represents the 95% certainty point in the LFT distribution. A sample LFT distribution is illustrated in Figure 7.11. The 95% certainty point was selected for two reasons. First, this point gives a good indication as to what time the component needs to be installed by to be reasonably certain that no unnecessary rework will be created regardless of the outfitting sequence of the other components. This allows an outfitting planner to quickly determine which components have the largest potential for causing disruptions in the outfitting process. Second, assigning the priority directly based on an installation time allows the direct comparison of priorities of components between different sections. This is important since mounting teams work on multiple sections simultaneously during the outfitting process.

7.5 Test Case

A test case was performed to evaluate the feasibility of the mathematical model and solution technique developed for the Detailed Outfitting Planning Method. This

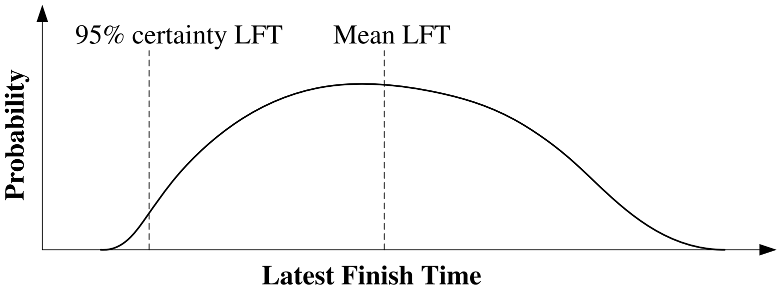


Figure 7.11: Sample LFT distribution for a component

case examines the construction of a pipelaying ship at Royal IHC, a Dutch shipyard. Table 7.1 describes the main characteristics of the test case.

Table 7.1: Test case characteristics

Length	146 m
Beam	30 m
Deadweight	11,300 tons
No. sections	112
No. rooms	440
No. tasks ($\|N\|$)	20,718
No. component groups ($\|G\|$)	2,690
No. installation path constraints ($\|P\|$)	6,461
No. working distance constraints ($\|Q\|$)	249,035
Task time limit for urgency (ϵ)	8 hours

Table 7.2 presents the outfitting disciplines and tasks considered for the test case. The items listed in this table represent the vast majority of outfitting tasks requiring hotwork to complete. The one exception is the electrical discipline, where the installation of cable trays under two inches was excluded. The installation of these small cable trays represents over two-thirds of this discipline's work. Unfortunately, the geometry of these trays was not modeled, and therefore it was not possible to include them.

Table 7.2: Considered outfitting disciplines

Discipline	Components
Piping	Pipe spools, valves, strainers, pumps, minor equipment
HVAC	Ducts, fans, minor equipment
Electrical	Cable trays, light fixtures, minor equipment
Secondary steel	Foundations, stairs, ladders, platforms, railings

Painting and insulation were not included because these two tasks are generally performed independently from the included tasks (Wei, 2012). Furthermore, large components (weighing more than 500kg) were excluded. This was done because the installation of such components is typically not done by the two man mounting team resources considered by the mathematical model. Furthermore, the planning of these components, such as the main engines and generators, is often dictated by the delivery schedule of the suppliers.

The base mounting time (b) of pipe spools, cable trays, and HVAC ducts were estimated using the equations developed by Wei (2012). In her research, Wei also determined the mounting time of roughly 100 pieces of equipment. A polynomial was fit through this data to estimate the mounting time of a piece of equipment from its mass. To determine the mounting times of secondary steel components, the total number of hours associated by the shipyard to these outfitting tasks was divided by the total mass of these components. An experienced outfitting supervisor was asked to estimate the mounting time of light fixtures.

Mounting time multiplication factors (ξ) were estimated using Schank et al. (2005) as guidance. Schank et al. (2005) surveyed four EU shipyards asking the yards to estimate these factors. The results of this survey were used as guidance for the authors to select the factors used for the test case. Factors of 1, 2, and 4 were chosen for pre-outfitting, slipway outfitting, and quay outfitting respectively. These factors also roughly match those used internally within the test case shipyard.

The required setup time (y) was taken to be 0 minutes if the mounting team was previously in the same work location (section or compartment), 30 minutes if the mounting team was in the same area (section assembly area, slipway, or quay), and 60 minutes otherwise. The setup time values were based on shipyard observation by the authors.

Because Royal IHC depends on subcontractors for the installation of cable trays and HVAC ducts, these components were not broken into small chunks suitable for mounting in the examined ship's 3D model. Instead, these components were modeled as entire lines. The methodology developed by Wei (2012) was used to break these lines into roughly 3 meter long pieces suitable for installation. Wei cites that the preferred installation size of HVAC ducts in the maritime industry corresponds with spools of roughly this size.

A distance of 2.5 meters, as proposed by Wei (2012), was used to generate the exclusion type precedence constraints to ensure a minimum safe working distance between mounting teams. Component deadlines (z) were based on the minimum of the painting date of that component's room and the latest point in time it was possible to transport a component into its room. This point in time was calculated using the methodology presented in Section 7.4.1. The start and finish times of each of the outfitting stages (Ψ) were taken from the Erection and Section Building Plan used for the actual construction of the test case ship.

7.6 Results

The developed methodology was coded in PL/pgSQL, the native scripting language of PostgreSQL. All trials were run on a single core of a 64-bit PC with 16 GB RAM and an 8x 3.50 GHz processor. A single iteration of the algorithm required roughly 24 hours to evaluate. However, it is most likely possible to vastly reduce the computational time through using a different software or more efficient programming. This is especially true for the queries related to selecting the component with the highest priority, which iteratively searched several massive tables joined together.

Figure 7.12 presents the resource distribution curves for the test case ship calculated using the developed methodology. The resource curves are included for each discipline as well as for the total outfitting process. Figure 7.12 also indicates the location of the time windows of each outfitting phase. A large overlap exists between pre-outfitting and slipway outfitting since section building and erection occur simultaneously. The launching milestone is also included. No outfitting occurs during launching.

The list scheduling algorithm is greedy by nature, and therefore it attempts to schedule tasks as early as possible. Figure 7.12 illustrates this effect, as the majority of the idle time is found at the end of the schedule. Idle time only exists at the beginning of the schedule if no eligible outfitting tasks exist at that time. The idle time at the end of the schedule exists due to the discrete nature of assigning a limited number of outfitting teams to a set of tasks. However, the large idle time at the end of the schedule is partially deceptive, since many components had deadlines prior to the end of the quay outfitting stage. This occurred since the deadlines are largely based on the rooms' painting schedules, which are somewhat staggered. The amount of idle time at the end of the schedule also appears exaggerated since components require four times as many man-hours to be installed during this stage.

The number of outfitting teams required matches the lower bound calculated for each discipline in the first step of the list scheduling heuristic. Therefore, this heuristic produced a high-quality outfitting plan. This is supported by the generally level nature of the resource curves. Level curves at maximum capacity indicate that the algorithm was able to assign a new task to each outfitting team as soon as they finished the previous task. The peaks at the end of the graph occurred when a certain discipline was mostly finished, with the exception of a few components that had precedence constraints other disciplines' components.

Figure 7.12 also indicates that only two mounting teams were required for the electrical discipline. Such a low number of teams were required due to the exclusion of cable trays under two inches (see Section 7.5). Unfortunately, including these trays was not possible in this study due to the absence of the required data.

Figure 7.13 shows the task distribution by man-hours for each of the outfitting disciplines. The combined task distribution for all disciplines is also included. This figure indicates the HVAC mounting teams were idle roughly 40% of the time. This occurred because the section building and erection process of the test case ship initially focused on the double bottom sections. These sections require almost no HVAC related tasks. This trend is also visible on Figure 7.12, where the HVAC mounting teams are not fully occupied until the 70th day of the outfitting process. Figure 7.13 also indicates that the mounting teams spent a very low percentage of their time moving between work locations (setup). This occurred since the priority rule of the list scheduling heuristic was designed to minimize setup time.

Figure 7.13 implies that the solution found for the test case ship has a very low pre-outfitting percent since only 25% of all outfitting man-hours were spent on pre-outfitting tasks. However, this percentage greatly underestimates the number of components installed in the pre-outfitting stage since work performed during this stage is much more efficient. Figure 7.14 presents the percentage of components installed

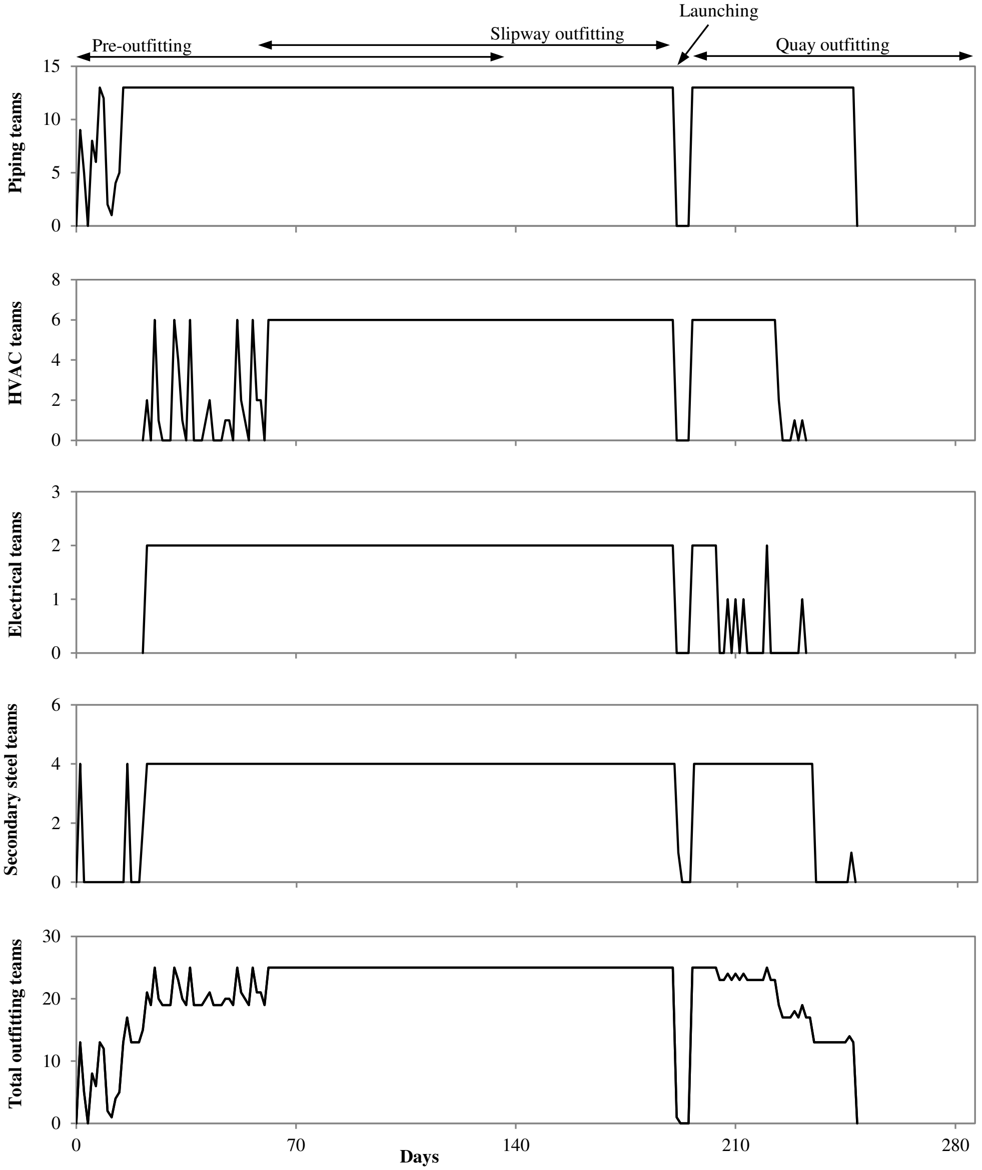


Figure 7.12: Resource distribution curves for base situation

in each outfitting stage by discipline. This figure indicates that the pre-outfitting percent is roughly 60%, comparable to modern shipyards building complex ships. Furthermore, the methodology designed in this chapter does not place an emphasis on maximizing pre-outfitting percent. Instead, the objective is to create a level resource demand. A higher pre-outfitting percent could be obtained by increasing the number of mounting teams early in the process. Such an improvement could be implemented by allowing the model to change the outfitting workforce size at one point

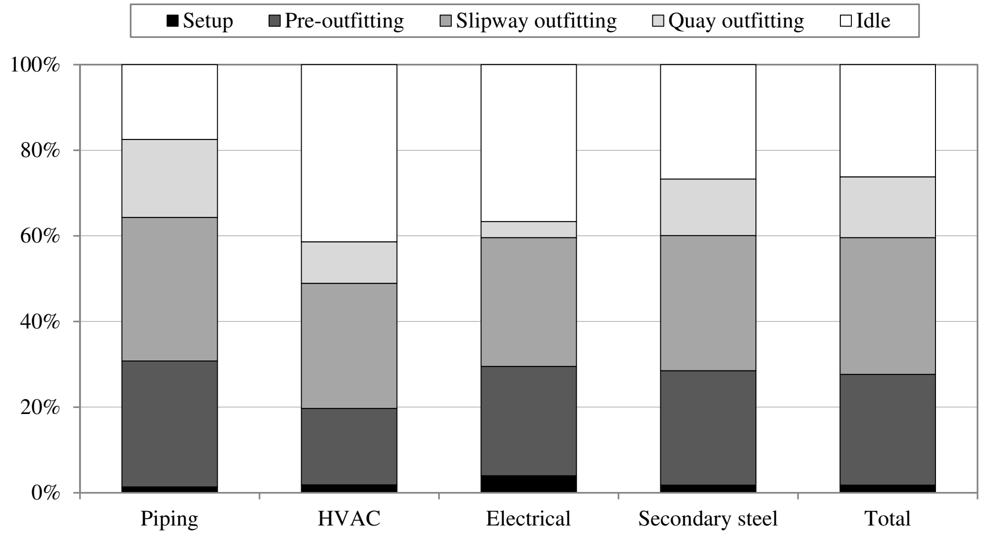


Figure 7.13: Task distribution by man-hours

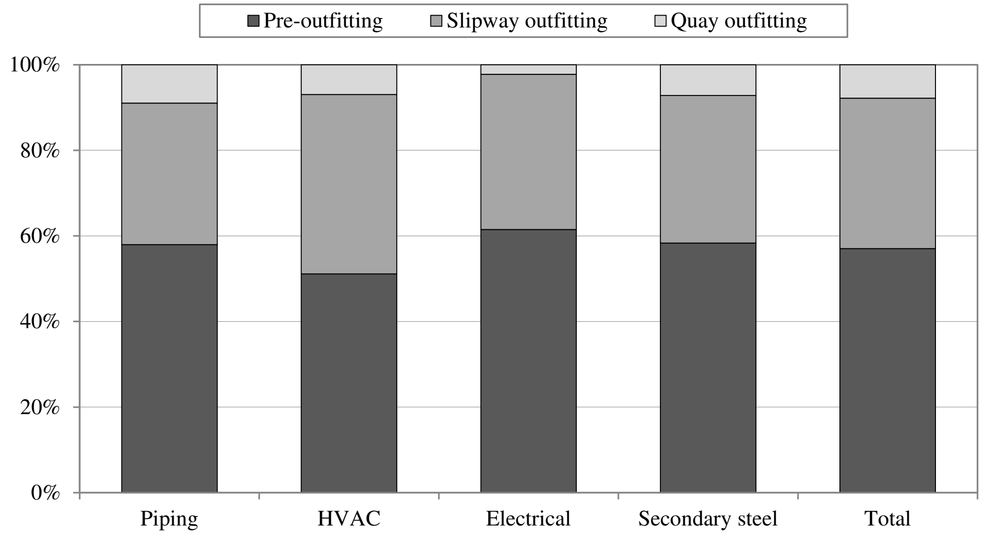


Figure 7.14: Outfitting stage distribution by number of components

during the shipbuilding process. This modification might also reduce the total number of man-hours required since pre-outfitting work is more efficient than slipway and quay outfitting work. However, the peak number of mounting teams required would be increased.

7.7 Validation

The Detailed Outfitting Planning Method was not validated to the same extent as the Erection and Section Building Planning Methods because a similar effort had already been performed by Wei (2012). Wei developed a method for generating a detailed Outfitting Plan for the components in a single section. This research was performed at the same shipyard that built the test case ship presented in this chapter. Wei's research was the starting point for the development of the Detailed Outfitting Planning Method. Overall, Wei found that it would be possible to use her method to plan outfitting tasks. Wei also individually validated many of the individual constructs composing her model, such as the mounting times of components, the feasibility of the assembly sequences, and plan duration. However, Wei received the following feedback while validating her method:

- **Include different outfitting stages:** Wei's method only considered a single section at a time, and assumed that all work was completed in the pre-outfitting stage. This issue has been addressed by the Detailed Outfitting Planning Method, as the different outfitting stages and interactions between the sections are central to the method. The Time Window Constraints guarantee that components are installed during one of the allowable outfitting stages.

- **Include the steel structure:** While developing her method, Wei did not have access to the ship's structural geometry. Therefore, the interferences between the outfitting components were defined in a vertical direction instead of in the normal direction to the closest steel boundary. The Detailed Outfitting Planning Method, however, fully considers the influence of structure on the allowable outfitting sequences through the 3D implementation of the Collision Free Installation Path Constraints.

- **Improve pipe constraints:** Wei's model did not include any constraints that prevented pipes from being installed between two already mounted pipes. Furthermore, it was possible to begin with spools other than penetration pieces in her model. The Installation Continuity Constraints of the Detailed Outfitting Planning Method were designed to address both of these shortcomings in Wei's model.

- **Include equipment-related constraints:** Wei's model did not sufficiently include constraints specific to the installation of equipment. For example, her model did not check if it was possible to place a piece of equipment in a room due to size restrictions. The Detailed Outfitting Planning Method checks this condition using the method developed in Section 7.4.1. However, other equipment related constraints, such as determining if crane capacity exists to transport the equipment, were also excluded from the Detailed Outfitting Planning Method.

7.8 Feedback to Erection and Section Building Plan

In general, the Erection and Section Building Plan used as input for the test case presented in this chapter supported a smooth execution of the outfitting process.

It was possible to complete the required outfitting work using a reasonable number of mounting teams. Furthermore, no major bottlenecks were created in the outfitting process, and no giant gaps or spikes exist in the resource curves presented in Figure 7.12.

However, the Outfitting Plan could potentially be improved with respect to the HVAC discipline. Figure 7.12 indicated that very little work existed for the HVAC mounting teams during the first seventy days of the process. The overall HVAC workload could have been distributed more smoothly if sections containing more HVAC work were assembled and pre-outfitted at the start of the process. However, this implies that these sections would either have to be placed earlier in the erection sequence or stored for a significant portion of time.

This same trend was also seen during the development of the Section Building Planning Method (see Chapter 5). One of the key differences between the examined production schedule created by the Section Building Planning Method and the one created manually by the shipyard planners was the distribution of HVAC workload (shown in Figure 5.11). The Section Building Plan used by the shipyard created a spike in HVAC work in the third quarter of the section building process. The solution produced by the Section Building Plan Method significantly reduced the size of this spike and moved a portion of the HVAC workload forward in the process. This demonstrates that the design of the Section Building Planning Method already considers the effects of outfitting to a significant extent and attempts to alleviate potential problems that may be encountered by the Detailed Outfitting Planning Method.

7.9 Implementation

Ultimately, the goal of the Detailed Outfitting Planning Method is to generate a high-quality Outfitting Plan that can be used as a starting point by shipyard planners. This type of implementation is similar to that of the Erection Planning Method and Section Building Planning Method (see Sections 4.8 and 5.8). To successfully implement the Detailed Outfitting Planning Method in a shipyard, several challenges must be addressed. First, mounting teams are currently not accustomed to working with such a detailed level of planning, but instead rely on their own experience and crude planning rules. Shipbuilding is a conservative industry, and implementing this drastic cultural change will be inherently met with resistance. Furthermore, the separate outfitting disciplines are often performed by independent subcontractors, each motivated by different factors. Without implementing a satisfactory incentive scheme, it will be very difficult to convince one subcontractor to hinder their own work process to benefit another subcontractor.

Furthermore, implementing the Detailed Outfitting Planing Method relies on having a sufficiently mature ship design available at the beginning of the production planning phase. However, current European shipyards building complex ships perform the design and production stages concurrently in an effort to minimize the total time required to construct a ship. This data availability problem is described in detail in Section 3.5. This section also describes how this problem may be mitigated in the near future through research focused on automated ship design tools.

Furthermore, an automatic detailed outfitting planning method can still benefit a shipyard even if it is not used for daily planning. This type of method can be used to help a shipyard make strategic decisions, such as the implementation of multi-skilled outfitting workers. Such an analysis is presented in Section 8.2. It can also be incorporated into a dynamic progress tracking tool. In this way, the shipyard can analyze the already completed work to predict future disturbances in the outfitting process. Lastly, the generated Outfitting Plan can be used as a centerpiece for discussion between the various stakeholders in the outfitting process. This would allow all parties to be more aware of the workload, challenges, and potential scheduling conflicts of the other outfitting disciplines.

7.10 Conclusion

This chapter develops the Detailed Outfitting Planning Method, the final module of the Integrated Shipbuilding Planning Method. To develop this module, the ship outfitting process was mathematically modeled as an expanded variation of the RACP. This variation included phase dependent task execution times, sequence dependent setup times, and complex precedence constraints. The deadline of each outfitting task depends partly on the latest point in time a component can be transported to a room based on size restrictions. Because this point in time is not commonly known for all components, a method was developed for automatically determining this value.

A custom list scheduling heuristic was developed to find a high-quality Outfitting Plan that satisfies the constraints of the mathematical model. Because the performance of list scheduling heuristics are highly dependent on the task priorities assigned a priori, a method was developed for determining these priorities specifically tailored for this application. This developed heuristic was able to find a high-quality Outfitting Plan for a test case of a pipelaying ship recently delivered from a Dutch shipyard. The computational time required to attain this production schedule was somewhat extensive (up to several days), but still feasible relative to the time required to build a ship.

Eventually, the Detailed Outfitting Planning Method could be used by a shipyard to guide the planning of its outfitting process. Such a plan could also be used by the shipyard as a coordination tool between the specialized outfitting subcontractors or as a reference for tracking the outfitting process of a ship. Several challenges currently hinder the direct implementation of this method, such as data availability and conflicting motivations between subcontractors. The first of these challenges would need to be addressed by changing the traditional information flow of a shipyard to focus more heavily on gathering, processing, and maintaining the necessary data. To address the second challenge, an implementation approach must be designed that is beneficial for every stakeholder. The method can also be used by a shipyard to asses strategic planning decisions related to outfitting. This type of analysis is presented in Section 8.2 of the following chapter, which determines the effect of implementing multi-skilled workers.

Chapter 8

Scenario Analysis*

The previous five chapters proposed and developed the Integrated Shipbuilding Planning Method, which automatically creates production schedules for the construction of complex ships. In these chapters, test cases are presented which compare the schedules produced by the method to those manually created by shipyard planners. This was done to show the benefits of directly implementing such a method in the planning process of a shipyard. However, the Integrated Ship Outfitting Planning Method can also be used to help a shipyard make strategic planning decisions for which limited data is available. This chapter describes two scenarios where the method is used to provide additional insight into such decisions.

The first scenario compares three different block building strategies. Currently, shipyard planners rely on historical data or personal experience to decide which sections should be combined to form blocks prior to erection. However, building blocks can significantly effect the erection and section building processes. This scenario uses the Combined Erection and Section Building Method to quantitatively assess the effect of the three different block building strategies on the production of a test case ship.

The second scenario examines the effect of introducing multi-skilled mounting teams on the outfitting process. Multi-skilled mounting teams can potentially increase the flexibility of the outfitting workforce and minimize the required number of personnel movements between different work sites. However, additional costs are associated with training and maintaining such a workforce. The Detailed Outfitting Planning Method is used to quantitatively determine some of the benefits of using multi-skilled mounting teams. This information can be used by a shipyard to help make the decision of whether the shipyard should pursue such an outfitting strategy.

8.1 Varying Block Definitions

A shipyard can potentially improve its erection process through the construction of blocks. Blocks are groups of sections that are welded together prior to erection. This allows these sections to be placed and fixed on the slipway as a single unit. Building

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*This chapter is partially based on Rose and Coenen (2016c).

blocks shifts work away from the slipway, which potentially allows for a more level erection workload and additional time for slipway outfitting. However, the blocks must also be produced. This can be done either on-site in the section building area or at the facilities of a subcontractor. When a block is built on-site, the block building process requires the same floor area that is required to build sections. This means that the space resources available for section building are negatively affected. When a block is built off-site, the total amount of outsourced work for the shipbuilding project is increased. Block building also slightly hinders the erection process since additional crane movements are required.

Block building is already included in the Combined Erection and Section Building Planning Method described in Chapter 6. A detailed, qualitative description of the block building process is included in this chapter. The terminology, mathematical model, solution technique, and test case presented in Chapter 6 are also used in this section. The test case described in Chapter 6 already includes four blocks made of different accommodation sections. This section examines the effect of implementing two alternative block production strategies, either building no blocks or building four additional blocks to form the closing decks above the ship's baskets. The Combined Erection and Section Building Planning Method is used to quantitatively compare these three block building strategies.

8.1.1 Literature Review

Only one work has been found in literature that uses a quantitative model to compare different block building strategies. Caprace et al. (2011) use a discrete event simulation to compare two different block building strategies for the midship of an LNG carrier built in Brazil. The simulation assessed the effect of the strategies on the required lead time and budget while keeping the available resources fixed. This study was performed partly to help the shipyard make a decision on whether to purchase a new gantry crane. Although this work cannot be directly applied, it shows the feasibility of implementing such a study in a real shipbuilding environment. An analysis of the literature supporting the development of the automatic planning method used to assess the different block building strategies is in Sections 4.1, 5.1, and 6.1.

8.1.2 Implementation

Three different block building strategies are analyzed and compared. The first (Base Strategy) matches the strategy actually used to build the test case ship. This strategy involves building four different blocks. These blocks are all part of the ship's superstructure. The second strategy (No Blocks Strategy) does not create any blocks. Each of a ship's sections are individually erected in this scenario. The last strategy (Basket Decks Strategy) adds four additional blocks to the Base Strategy. These blocks form the decks covering the ship's pipe storage baskets. The Basket Decks Strategy matches the block building strategy of several of the test case ship's sister ships. Table 8.1 presents the block building characteristics specifically relevant to each of the strategies. More information of the test case used to compare the block building strategies is in Sections 4.5, 5.5, and 6.5.

To compare the different block production strategies, the Combined Erection and

Table 8.1: Block building strategy characteristics

	Base	No Blocks	Basket Decks
Number of blocks ($\lvert K \rvert$)	4	0	8
Number of block building tasks ($\lvert B \rvert$)	18	0	26

Section Building Method was first directly implemented for each strategy. This analysis is referred to as the Three Objective Analysis. This analysis creates a Pareto surface of potential production schedules, allowing the trade-offs between the three objectives (Resource, Outfitting, and Outsourcing Objectives) to be examined. This analysis also indicates to a shipyard which of the three strategies should be followed if the shipyard desires to improve their production process relative to one of the objectives.

Unfortunately, it is very difficult to directly compare the different block building strategies using the Three Objective Analysis because each strategy will most likely have superior performance in some region of the Pareto surface. To quantitatively compare the strategies, it is necessary to know how a shipyard values the relative importance of the three considered objectives. This information is heavily subjective and no data was found to scientifically estimate these relationships. However, the general opinion of the planners at the test case shipyard was that having level resource requirements (Resource Objective) was the most important of the three objectives. This opinion was the basis of the second analysis performed, the Single Objective Analysis. The Single Objective Analysis seeks to minimize the Resource Objective while treating the Outfitting and Outsourcing Objectives as constraints. For this analysis, a production schedule is only considered valid if the Outfitting and Outsourcing Objectives are less than or equal to those achieved by the shipyard when actually constructing the test case ship. This guarantees that the production plan produced by the optimization has historically acceptable values for both objectives. To perform the Single Objective Analysis, minor modifications were required to the mathematical model and methodology described in Sections 6.3 and 6.4 respectively. The following notation is used:

$O_{res(C)}$	Resource Objective
O_{outf}	Outfitting Objective
O_{outs}	Outsourcing Objective
O'_{outf}	Outfitting Objective of production schedule actually used
O'_{outs}	Outsourcing Objective of production schedule actually used
V_{outf}	constraint violation of Outfitting Objective
V_{outs}	constraint violation of Outsourcing Objective
M	arbitrarily large number

Two additional constraints, Equations 8.1 and 8.2 respectively guarantee that the Outfitting and Outsourcing Objectives are less than or equal to those of the production schedule actually used to construct the test case ship.

$$O_{outf} \leq O'_{outf} \tag{8.1}$$

$$O_{outs} \leq O'_{outs} \tag{8.2}$$

An additional step, described by Equation 8.3, is added to the fitness function (described in Figure 6.3). This step sets the Resource Objective to its actual value if Equations 8.1 and 8.2 are satisfied. If either of these constraints are violated, however, the Resource Objective is set to be arbitrarily large. The size of the Resource Objective is proportional to the degree of constraint violation.

$$O_{res(C)} = \begin{cases} O_{res(C)} & \text{if } V_{outf} = 0 \land V_{outs} = 0 \\ M + V_{outf} + V_{outs} & \text{otherwise} \end{cases} \tag{8.3}$$

where V_{outf} and V_{outs} are calculated by Equations 8.4 and 8.5 respectively

$$V_{outf} = \begin{cases} O_{outf} - O'_{outf} & \text{if } O_{outf} > O'_{outf} \\ 0 & \text{otherwise} \end{cases} \tag{8.4}$$

$$V_{outs} = \begin{cases} O_{outs} - O'_{outs} & \text{if } O_{outs} > O'_{outs} \\ 0 & \text{otherwise} \end{cases} \tag{8.5}$$

8.1.3 Results

To perform the Three Objective Analysis, 100 trials were run for each of the block building strategies. Such a high number of trials were performed due to the inconsistent behavior of the NSGA-II when solving the combined erection and section building mathematical model (see Section 6.5). A Pareto surface was created for each of the block building strategies from the combined set of the solutions of the 100 trials. To visualize the Pareto surface, three Pareto fronts were created, presented in Figures 8.1 to 8.3. These figures contain the best solutions found for two of the objectives, and the third objective is taken as a cutoff constraint. The value used as the cutoff point was the value of the third objective for the plan actually created by the shipyard planners. Therefore, all of the solutions included in Figures 8.1 to 8.3 were at least as good as the plan actually used to build the test case ship with regards to the objective not examined in the figure.

Figure 8.1 compares the Pareto fronts for the Resource and Outfitting Objectives. This figure indicates that although all three block building strategies found solutions with similar Resource Objectives, the Basket Decks Strategy had significantly superior performance with respect to the Outfitting Objective. This occurred since this strategy produced the highest number of blocks. Having additional blocks results in fewer erection tasks, which means that these tasks can be spaced further apart. Furthermore, the NSGA-II has more freedom to arrange these tasks in an optimal fashion. Both of these factors allow for erection schedules with more time available for slipway outfitting of densely packed spaces.

The Pareto fronts for the Resource and Outsourcing Objectives are compared in Figure 8.2. The figure also shows that the NSGA-II was able to find solutions of comparable Resource Objective Values for all three block building strategies. However, the No Blocks Strategy had the best performance for the Outsourcing Objective. This occurred since building blocks inherently forces a shipyard to increase the amount of

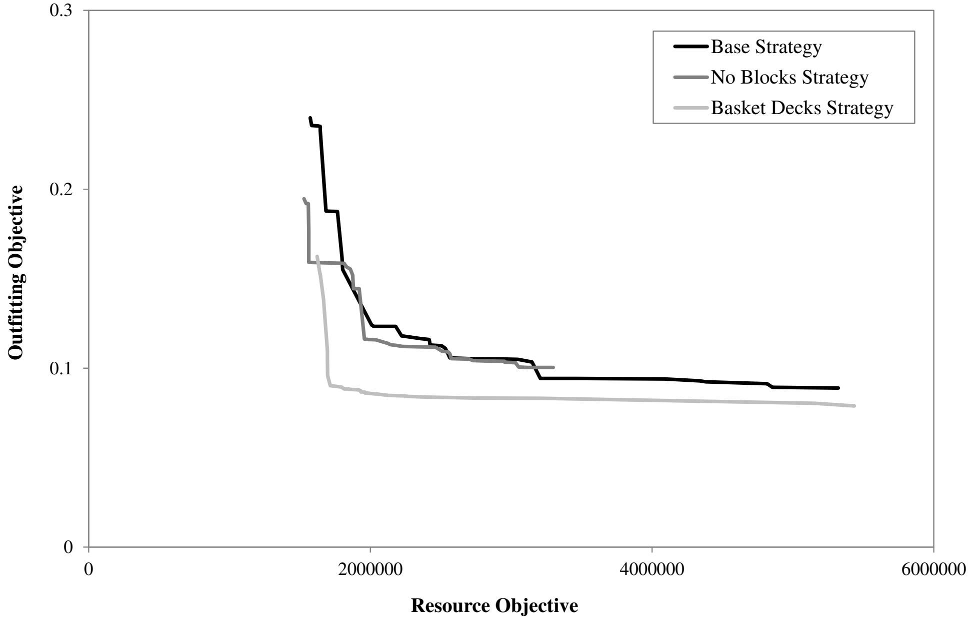

Figure 8.1: Pareto fronts for block building strategies, $O_{outf} \leq 0.307$

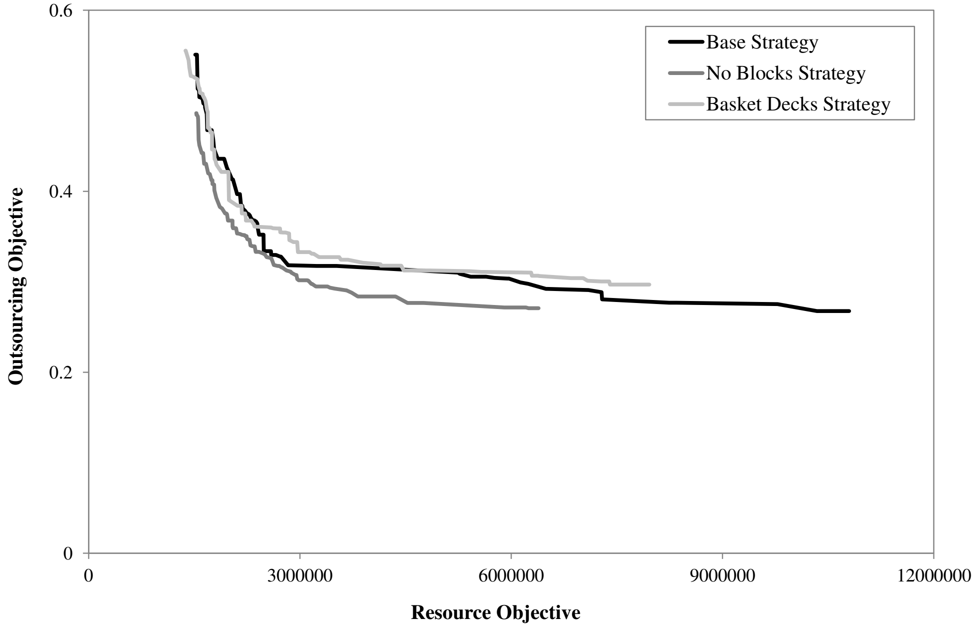

Figure 8.2: Pareto fronts for block building strategies, $O_{outs} \leq 0.506$

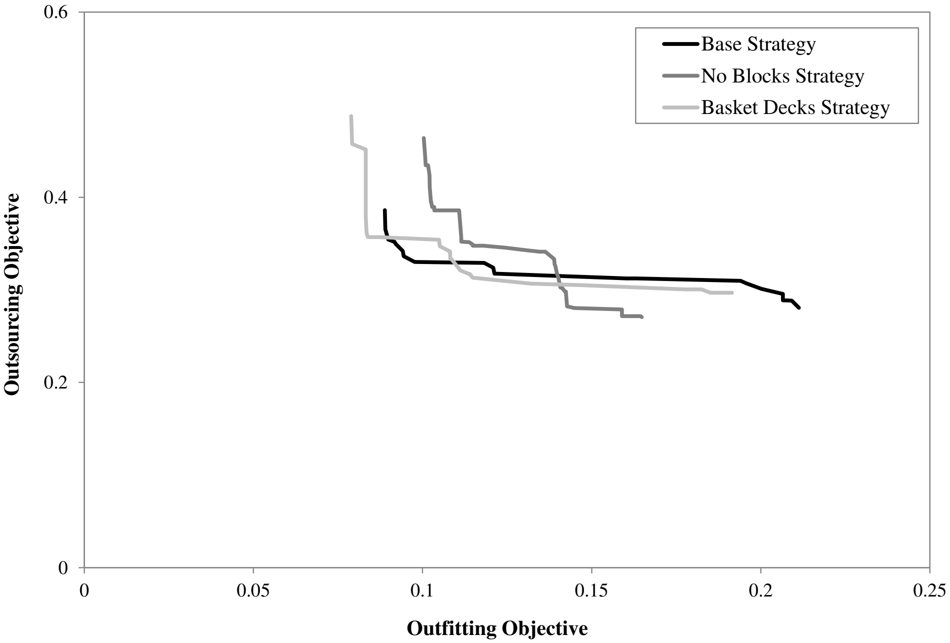

Figure 8.3: Pareto fronts for block building strategies, $O_{res} \leq 8200000$

outsourced work. When blocks are built off-site, the number of erection man-hours outsourced increases. When blocks are built on-site, less floor space is available to the section building process, increasing the number of sections which must be outsourced.

Figure 8.3 presents the Pareto fronts for the remaining two objectives, the Outfitting and Outsourcing Objectives. This figure reinforces the trends shown in the previous two figures. The Basket Decks Strategy resulted in the best performance with respect to the Outfitting Objective, and the No Blocks Strategy resulted in the best performance for the Outsourcing Objective. Figures 8.1 through 8.3 also indicate that the Base Strategy represents a compromise between the other two strategies, having mediocre performance with respect to all three objectives.

The Three Objective Analysis illustrates the trade-offs between selecting a block building strategy and the performance of each of the objectives. This type of information can be used to guide a shipyard when making strategic decisions. For example, if a shipyard wants to improve its slipway outfitting process, the shipyard should consider building additional blocks in upcoming projects. However, the Three Objective Analysis does little to directly compare the performance of the scenarios. This type of comparison is done by the Single Objective Analysis, which assumes a shipyard is mainly focused on the Resource Objective. For this analysis, the other two objectives are treated as cutoff constraints from the beginning.

To perform the Single Objective Analysis, 100 trials were run for each of the block building strategies using the modified mathematical model and solution technique presented in Section 8.1.2. Figure 8.4 compares the best value of the Resource Objective for the best solution found for each of the Block Building Strategies. This

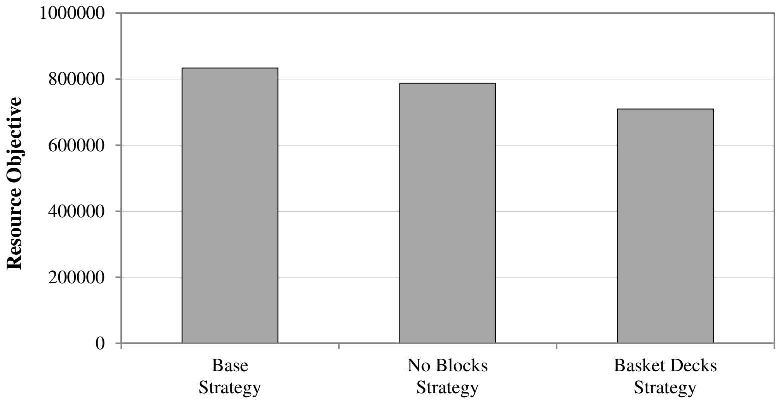

Figure 8.4: Best solution of Single Objective Analysis

figure indicates that the Basket Decks Strategy had the best performance of the three examined block building strategies. Therefore, if a shipyard is mainly concerned with having level resource curves, the shipyard should follow this block building strategy when building the test case ship.

8.1.4 Conclusion

The Combined Erection and Section Building Method was used to analyze the effect of block building strategies on the production process of shipyards building complex ships. Two analyses were performed. The first showed that while increasing the number of blocks built improves the slipway outfitting processes, this decision also increases the number of outsourced man-hours. The second determined which specific block building strategy would be best for a shipyard mainly concerned with having level resource curves. Performing the scenario of varying block divisions demonstrated that it is possible to use the Combined Erection and Section Building Method module of the Integrated Shipbuilding Planning Method to help shipyards make strategic planning decisions related to erection and section building.

8.2 Multi-skilled Outfitting Workers

The outfitting process of complex ships could be potentially improved by implementing multi-skilled workers. These types of mounting teams allow a shipyard to resolve temporary resource shortfalls and over-capacities of certain disciplines by shifting workers between disciplines (Hegazy et al., 2000). This reduces some of the overloads and idle times inherently present when using a single skilled workforce (Liu and Wang, 2012), resulting in a more flexible workforce. For example, shipyards typically begin building a ship by assembling and erecting double bottom sections. Such sections require almost no HVAC ducting. If the HVAC ducting mounting teams were also capable of installing piping, they could still contribute during this phase of production.

Furthermore, multi-skilled workers are generally more aware of the total shipbuilding process. Stravinski (1989) found that such workers received more information about the work being done in their vicinity which helped them perform their job better. Implementing multi-skilled workers can also reduce the number of different personnel required in a space, resulting in less crowding and interferences (Nallikari, 1995). Not only is crowding potentially reduced, but fewer personnel movements between work sites are also potentially required. Consider a room with a few piping and electrical tasks. These tasks can be completed by either one multi-skilled team or two specialized ones. If multi-skilled workers are used, these tasks require half the initial personnel movement.

Overall, multi-skilled workers can help smoothen the required work flow (Storch, 1999). For example, if a single-disciplined worker encounters a mistake of a different discipline that is hindering his own task, they must find someone else to address the situation. Multi-skilled workers can fix this type of conflict themselves. Moreover, multi-skilled workers can better cover for each other when one of their colleagues is sick or otherwise absent (Nallikari, 1995). Overall, the benefits of using multi-skilled workers are greater for jobs requiring a high degree of coordination and communication (Stravinski, 1989), a characteristic typical of outfitting complex ships.

However, several disadvantages also exist for implementing multi-skilled workers in shipbuilding. Labor unions potentially hinder the effective sharing of labor between disciplines (Stravinski, 1989). Hegazy et al. (2000) cite two examples of the interaction between unions and shipyards trying to implement such workers, a positive case from a Canadian shipyard and a negative case from an American shipyard. Similar problems could also potentially arise between different specialized subcontractors who end up competing for the same workload. Ultimately, these type of disagreements should be resolvable in the long term if the benefits of a multi-skilled workforce are sufficiently high enough.

Although using a multi-skilled workforce potentially smoothens the work flow of a shipyard, such workers can also have the opposite effect. The supervision of these employees becomes more difficult (Stravinski, 1989), and the effectiveness of the shipbuilding process becomes more dependent on a foreman's ability to allocate work and design well-balanced teams (Liu and Wang, 2012). Furthermore, the multi-skilled workers themselves can struggle to identify with their role in the shipyard (Stravinski, 1989).

Additional training is also required to effectively use multi-skilled workers. This is particularly prohibitive for some trades, such as electricians, who are highly specialized (Stravinski, 1989). This disadvantage is exactly the reason that most shipyards building complex ships have selected to implement a highly specialized, single-skilled workforce. Implementing a multi-skilled workforce undoes a large part of the competitive advantage these shipyards have gained with this strategic decision. It also becomes more difficult to outsource work requiring multi-skilled workers. However, significant skill overlap exists between certain outfitting disciplines. For example, a proficiency in welding and burning is required for both pipe fitters and sheet metal fitters.

The scenario presented in this section examines the effect of implementing multi-skilled workers using the Detailed Outfitting Planning Method developed in Chapter 7. No modifications were required to the mathematical model and solution technique beyond modifying the disciplines to which some of the outfitting tasks were assigned. The benefits of multi-skilled mounting teams were assessed using the same test case as the one used to assess the Detailed Outfitting Planning Method. Six different multi-skilled strategies were examined, each representing two of the included outfitting disciplines grouped together.

8.2.1 Literature Review

The implementation of multi-skilled workers has been addressed by several works from shipbuilding literature. Nallikari (1995) examines the use of multi-skilled, independent work groups in a Finish shipyard which was shifting its outfitting strategy from system outfitting to zone outfitting. Nallikari concluded that such work groups result in a significant decrease in throughput time and increase in job productivity. In a similar study, Stravinski (1989) examines the use of multi-skilled, self-managing work teams in an American shipyard using zone outfitting. Storch (1999) and Koenig et al. (2002) investigate the use of lean manufacturing techniques in shipbuilding and these authors mention multi-skilled workers as vehicles for implementing lean concepts.

Furthermore, research in theoretical scheduling has examined multi-skilled workers. These works generally modify classical optimization problems, such as the RCPSP, to allow some portion of the workforce to perform tasks of several disciplines. Examined solution techniques include mixed-integer programming (Heimerl and Kolisch, 2010), constraint programming (Liu and Wang, 2012), and heuristics (Hegazy et al., 2000; Wongwai and Malaikrisanachalee, 2011).

8.2.2 Implementation

The benefits of implementing multi-skilled workers in a shipyard building complex ships are examined using the mathematical model and solution technique developed in Sections 7.3 and 7.4 respectively. To examine this effect, certain outfitting disciplines were grouped together prior to performing the optimization. The assumption was made that any outfitting task previously performed by either of these disciplines could now be completed by one of the multi-skilled mounting teams. The test case ship described in Section 7.5 was used to assess this scenario.

This analysis examines some of the potential benefits of multi-skilled workers, including the reduction of personnel movements and increasing the flexibility of resource allocation. However, this approach does not address the intangible advantages and disadvantages, such as the requirement for better supervision or increased employee awareness of their surroundings. The scenario where multi-skilled workers affect the total working efficiency of mounting teams due to such intangible reasons is examined by modifying the base duration of outfitting tasks completed by multi-skilled workers.

8.2.3 Results

Six different strategies were tested to determine the influence of implementing multi-skilled workers. For each strategy, two of the outfitting disciplines were combined to form a single discipline. Figure 8.5 contains the resource allocation for each multi-skilled strategy as well as for the base situation. This figure indicates the number of

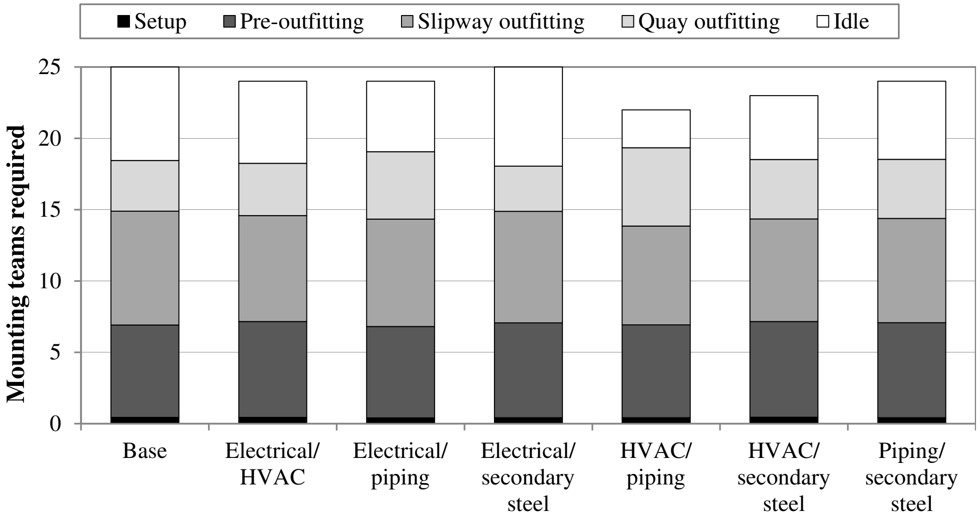

Figure 8.5: Resources allocation for multi-skilled strategies (goal of minimizing mounting teams)

mounting teams required to complete each strategy. The average task distribution over all of the disciplines is also included.

Figure 8.5 indicates that all multi-skilled strategies required fewer mounting teams than the base situation with the exception of the electrical/secondary steel strategy, which required the same number of mounting teams. The best strategy was the HVAC/piping strategy, which required three less mounting teams. Figure 8.6 examines this strategy in more detail, comparing the total resource distribution curves of this strategy to the base situation. This figure shows that the HVAC/piping strategy had more level resource curves, indicating that this strategy was able to better utilize the available outfitting resources over the entire outfitting process. The HVAC/piping strategy had the best performance for two reasons. First, the HVAC discipline had the most to gain from multi-skilled workers because this discipline had the worst resource distribution curve (indicated in Figure 7.12). Second, the piping discipline was the largest discipline and therefore also the most flexible, enabling it to most efficiently integrate the uneven HVAC workload with its own tasks.

Figure 8.5 also shows that although the base situation required the highest number of mounting teams, the number of productive man-hours required was very low. On the other hand, the HVAC/piping strategy, which needed the least number of mounting teams, required the highest number of productive man-hours. This occurred since it was 400% more efficient to perform outfitting work during pre-outfitting, and the base situation had the most teams available to do work during this stage. Unfortunately, this also implies that these same resources would be idle at the end of the outfitting process, seen by the increased idle time in Figure 8.5. To illustrate this effect, Figure 8.7 compares the resource allocation for each of the strategies when the number of mounting teams was fixed to the levels required by the base situation. This figure indicates that the base situation has the highest number of active out-

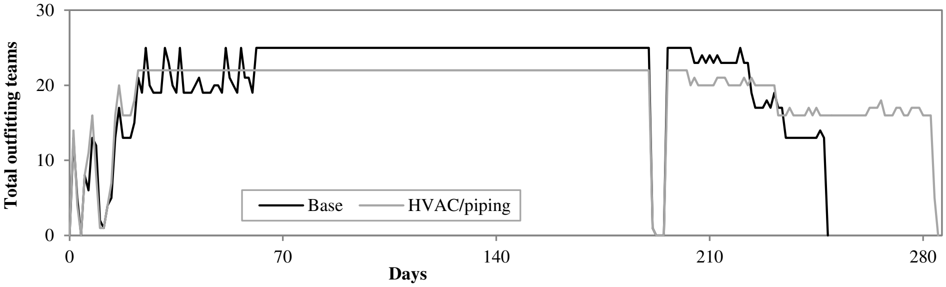

Figure 8.6: Comparison of total resource curves for base situation and HVAC/piping strategy

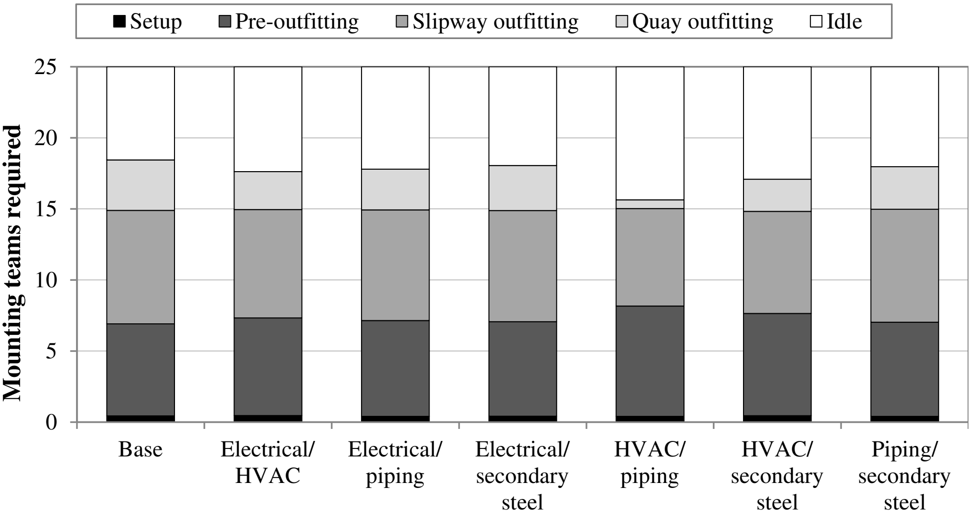

Figure 8.7: Resource allocation for multi-skilled strategies (fixed number of mounting teams)

fitting man-hours when the number of mounting teams is fixed. Furthermore, the HVAC/piping strategy has the least number of active outfitting man-hours, highest pre-outfitting percent, and almost no quay outfitting work. This is the same strategy requiring the least number of mounting teams in Figure 8.5. To fully reap the benefits of a high pre-outfitting percent and the flexibility of a multi-skilled workforce, an intermediate point should be defined where it is possible to adjust the workforce size.

One potential benefit of implementing multi-skilled workers is the reduction of personnel movements between work sites. This benefit is difficult to examine in Figure 8.5 due to the relatively low percentage of time the mounting teams spent on the setup task. Figure 8.8 compares the number of hours required for movements between different work sites for the base situation and each of the multi-skilled strategies. This figure indicates that although implementing multi-skilled workers reduced the required setup time, the reduction was negligible. The reason for this is twofold. The setup

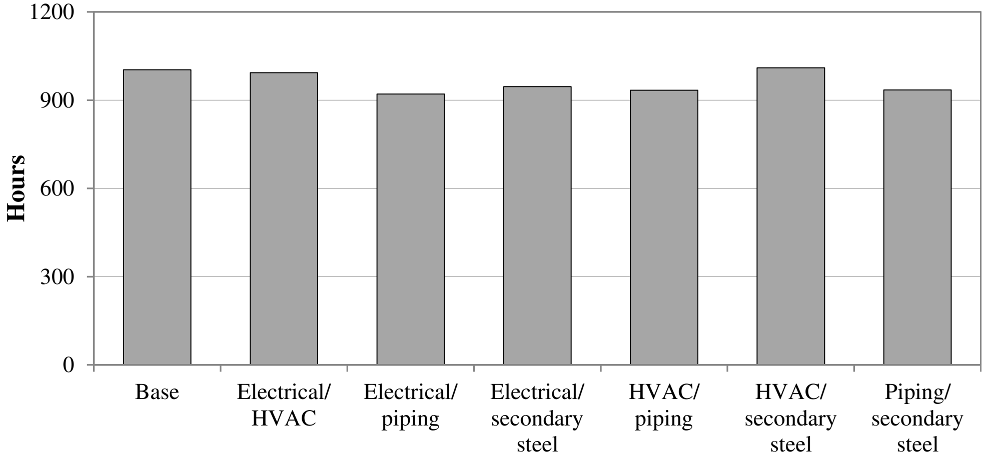

Figure 8.8: Setup time required for multi-skilled strategies

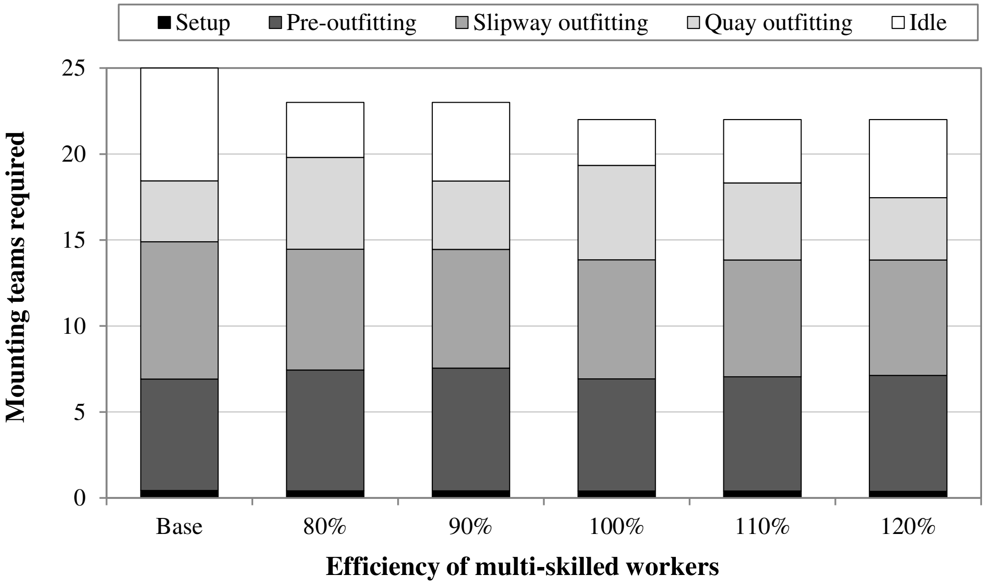

Figure 8.9: Resource allocation for HVAC/piping strategy

time represents such a small portion of the total outfitting man-hours, and the priority rule for the list scheduling heuristic already proficiently minimizes the required setup time. However, there is no guarantee that actual mounting teams will work to minimize setup time as efficiently as the list scheduling heuristic.

The analysis performed on the implementation of multi-skilled workers only considers two influences of these workers: the increased flexibility of work allocation and the reduction of setup time. However, many less tangible advantages and disadvantages of multi-skilled workers also exist, described in Section 8.2. The influence of these factors was tested by varying the efficiency of the multi-skilled workers. Workers with lower efficiency required additional time to perform the required outfitting tasks. Figure 8.9 presents the resource allocation for the HVAC/piping strategy with varying efficiencies of the multi-skilled workers. The base situation is also included for reference. This figure indicates that changing the efficiency of the multi-skilled workers has a much smaller effect than implementing them. Noticeable improvements in the outfitting process are still seen when the multi-skilled workers take an additional 20% time to complete the required mounting tasks.

8.2.4 Conclusion

The Detailed Outfitting Planning Method was used to analyze the effect of introducing multi-skilled workers into a shipyard building complex ships. This analysis concludes that although multi-skilled workers can effectively increase the flexibility of workforce allocation, these workers have a negligible impact on reducing the required personnel movements between work sites. Furthermore, implementing multi-skilled workers has a much greater effect on the outfitting process than the efficiency gains or losses of those personnel. It is still possible to find improvements when the multi-skilled workers perform tasks at 80% of the speed of single-skilled workers. This scenario demonstrates that it is possible to use the Detailed Outfitting Planning Method module of the Integrated Shipbuilding Planning Method to help shipyards make strategic planning decisions related to outfitting.

Chapter 9

Conclusions and Recommendations

This dissertation develops a method for automatically planning the production process of European shipyards building complex ships. This chapter reflects upon this effort and provides suggestions on how to further develop this approach. First, the overall conclusions of the research are discussed. These conclusions build upon the individual conclusions of the research components presented in Chapters 4 through 8. Next, the limitations of the research are examined. Not only do these limitations indicate the applicability of the approach, but they also provide guidance on where to best concentrate future research efforts. Lastly, recommendations are provided. This chapter contains two sets of recommendations. The first set indicates additional areas of research that could be done to improve the developed planning method, and the second set provides guidance to any shipyard planning to implement such a method.

9.1 Conclusions

Automatic production planning can potentially mitigate some of the main problems facing European shipyards building complex ships. However, to maximize the effectiveness of such an approach, a fully integrated method must be created which considers all relevant portions of the shipbuilding process: erection, section building, and outfitting. Having a centralized outfitting plan available at the beginning of the outfitting process would help alleviate the lack of organization and lack of transparency prevalent in the outfitting process of European shipyards. This plan could be used as a centerpiece for communication between the shipyard and subcontractors to ensure that each party understands which tasks should be completed at what times, reducing the amount of delays and rework. The problem of sub-optimization is also addressed since the integrated plan would be created by a method that seeks to optimize the process globally, instead of being biased towards the needs of the shipyard, owner, or any subcontractor.

Furthermore, creating such an integrated planning method makes the tacit knowledge of the shipbuilding process possessed by experienced employees explicit. This potentially mitigates the loss of industry specific skill resulting from an aging workforce present in European shipyards. Extracting the underlying constraints and objectives that govern the erection, section building, and outfitting process also addresses the lack of mathematical definition that exists for the construction of complex ships. Developing algorithms to generate these optimized production schedules increases the currently limited body of knowledge related to automatically scheduling shipbuilding tasks, specifically those related to outfitting.

This dissertation explored the creation of such an automatic production planning method. The purpose of the method was to automatically schedule the erection, section building, and outfitting processes of a European shipyard building complex ships. The following two research questions were designed to guide this effort:

> **Research Question #1:** Is it possible to develop a method for automatically generating an integrated erection, section building, and outfitting plan for European shipyards building complex ships?
>
> **Research Question #2:** How can developing such an integrated planning method benefit these shipyards?

To answer the first question, the Integrated Shipbuilding Planning Method was created. This method uses the characteristics of a shipyard, the geometry of a ship, and major project milestones to generate an integrated erection, section building, and outfitting plan. This novel method is the first automatic planning approach developed for the shipbuilding industry that fully incorporates the outfitting process. This method is also the first example of an automatic scheduling approach that is capable of simultaneously scheduling the erection and section building processes. The method is composed of three main modules: the Erection Planning Method, Section Building Planning Method, and Detailed Outfitting Planning Method. Each of these modules was independently evaluated using a test case of a pipelaying ship recently delivered from a Dutch shipyard.

To develop the Integrated Shipbuilding Planning Method, a mathematical model of the shipbuilding process was defined. This model was created by synthesizing existing literature, expert opinion, and an analysis of the operations of a typical European shipyard. The geometric, operational, and temporal relationships that constrain the shipbuilding process were defined in this mathematical model. Because some of these constraints were not readily available, techniques were developed for automatically extracting these relationships from existing data. The objectives used to measure the quality of a production plan were also explicitly defined in the mathematical model.

The Erection Planning Method uses a ship's geometry, a shipyard's characteristics, and a project's production milestones to generate a plan of the erection process. The Section Building Planning Method automatically creates a production schedule of the section building process using a ship's geometry, a shipyard's characteristics, and an Erection Plan (which is generated by the Erection Planning Method). The input data required for both of these methods matches the information to which shipyard planners have access when drafting the initial Erection and Section Building Plan of a new project. Both of these planning methods were able to create feasible production schedules for the test case ship in negligible computation time.

The interaction between the erection and section building processes was examined by creating a fourth module: the Combined Erection and Section Building Method.

This module simultaneously solved the Erection and Section Building Planning Methods, preventing the sub-optimization which occurs by executing these two modules sequentially. The Combined Erection and Section Building Method module also successfully produced an Erection and Section Building Plan for the test case ship in negligible computation time.

A multi-objective genetic algorithm was used to find high-quality solutions for the first three modules of the Integrated Shipbuilding Planning Method. A priority-based heuristic was used as a fitness function for the genetic algorithm. Although this approach does not guarantee that the optimal solution is found, it was able to find high-quality solutions in reasonable computational time. Due to the low computational requirements, it would be feasible for a shipyard to use these three modules of the Integrated Shipbuilding Panning Method reactively. With a reactive implementation, the production schedules of a ship would be frequently updated in real time to account for delays and disturbances. The run time of the automatic scheduling method must be negligible for this type of implementation to be effective.

The Detailed Outfitting Planning Method creates a detailed outfitting plan for a ship based on its geometry and a shipyard's characteristics. This module also requires the time windows during which each component can be installed as input. These time windows are taken from the project milestones, Erection Plan, and Section Building Plan. The latter two are generated by the Erection and Section Building Planning Methods respectively. A high level of geometric detail is required for this module because the Detailed Outfitting Planning Method works on the component level. Unfortunately, this detailed geometry is not fully available prior to the start of a ship's construction due to the production processes of modern European shipyards and the concurrent nature of the detailed engineering.

A list scheduling heuristic was used to find solutions for the Detailed Outfitting Planning Method. Although list scheduling heuristics do not necessarily find the optimal solution, these algorithms tend to perform well in loosely constrained problems, such as the scheduling of outfitting tasks. The Detailed Outfitting Planning Method was able to create a feasible detailed Outfitting Plan for the test case ship. Although this algorithm has very low computational requirements, a somewhat extensive computational time was required. Days of computation were necessary to produce a plan for the examined test case ship. This occurred due to the large number of outfitting tasks required to build a complex ship. Due to these excessive computational times, it would not be feasible to use the Detailed Outfitting Planning Method to reactively make changes to a production schedule.

The influence of the outfitting process on erection and section building was incorporated by generating feedback from the Detailed Outfitting Planning Method to the Erection and Section Building Methods. Fully integrating the Detailed Outfitting Planning Method with the other two modules was not practical due to the discrepancies in the level of detail required from the input data and the computational time required to produce a plan.

To answer the second research question, two subquestions were examined. Each of these sub-questions examined a potential benefit of implementing an automatic planning method in a European shipyard building complex ships. The second research question was considered to be sufficiently addressed when these two subquestions were satisfactorily answered.

> **Research Subquestion #2.1:** How do the integrated production plans created automatically by the developed method compare to those manually created by shipyard planners?
>
> **Research Subquestion #2.2:** How can the developed automatic planning methodology be used to improve the production process of these shipyards?

The first subquestion was answered by using the same test case as was used to answer the first research question. The production schedules created by the Erection and Section Building Planning Methods were directly compared to those created manually by the shipyard planners. The Section Building Planning Method produced schedules with more level resource requirements and outsourced fewer man-hours. The Erection Planning Method generated schedules with more level resource requirements and time available to perform slipway outfitting. Furthermore, both methods were able to produce a wide variety of potential solutions.

For outfitting, it was not possible to compare the plan created by the Detailed Outfitting Planning Method to the one created by the shipyard since European shipyards do not currently generate outfitting production schedules at such a detailed level. Such detailed outfitting schedules do not exist for the same reason the detailed geometric input data required for the Detailed Outfitting Planning Method is not available prior to the start of production. However, having a plan available was deemed to be superior to not having access to such a plan. The ability to generate a high-quality outfitting plan also further motivates shipyards to generate the required data in a timely matter for future projects. Furthermore, the effects of outfitting were globally considered by the Erection and Section Building Planning Methods at the same level of detail that is currently being used by shipyard planners.

The Integrated Shipbuilding Planning Method was used to examine two production scenarios to answer the second subquestion. The Combined Erection and Section Building Method was used to compare three different block building strategies. This analysis determined the effect of these strategies on the quality of the Erection and Section Building Planning of the test case ship. A recommendation was also given for the optimal scenario assuming the shipyard prioritized having a level resource demand. The effect of the implementation of multi-skilled workers on the outfitting process was examined using the Detailed Outfitting Planning Method. This scenario determined the effect of six different types of multi-skilled mounting teams on the total number of mounting teams required to build the test case ship. In both cases, the scenario analyses provided additional, useful information which could aid a shipyard in making strategic decisions.

This dissertation was designed to be a guide to be used by any shipyard wishing to implement an integrated automatic planning method in their production process. Such a shipyard will still need to adapt this work to their own process by incorporating their own production data; modifying the constraints and objective to match their production process; tuning the parameters of the solution technique; and implementing the result in the work flow of their planners. However, the global approach and algorithms underlying the solution technique should be directly applicable. Implementing the Erection and Section Building Planning Methods should be relatively straightforward, as these methods work with the same data (both input and output) as the shipyard planners drafting the initial production schedules. Furthermore, the negligible run time of these methods allows the planners to quickly make adjustments and test different scenarios. On the other hand, full implementation of the Detailed Outfitting Planning Method in a shipyard is limited by extensive computational requirements and the simultaneous nature of the engineering and production processes of European shipyards. Until the detailed geometry of a ship is available prior to the start of production, this method will be most useful for supporting strategic decisions and as a tool for improving the communication between the different stakeholders of the outfitting process.

9.2 Limitations

This section describes the limitations of the research presented in this dissertation. These limitations affect both the development of the approach and its implementation in a shipyard. Some of the recommendations presented in the following section are designed to address these limitations.

- **Data availability:** The effectiveness of any method seeking to optimize a process is inherently limited by the quality of the data provided to the model. Unfortunately, not all of the information required for the developed method is readily available in European shipyards. A significant effort was required to gather, analyze, and pre-process all of the data necessary to perform the test cases presented in this dissertation. Ultimately, the cost of performing and maintaining this data collection effort must be significantly less than the benefit provided for an automatic planning method to be effective.

- **Shipbuilding method:** The automatic planning methodology presented in this dissertation was tailored specifically to shipyards that rely heavily on outsourcing to complete production tasks. While many European shipyards building complex ships use this approach, other shipbuilding methods exist. For example, some shipyards aim to maximize their control over their production processes by developing as many skills as possible in-house. Although the underlying algorithms of the developed methodology are still applicable for this situation, significant adjustments must be made.

- **Human judgment:** The judgment of the shipyard planners is integral to the successful implementation of the automatic planning methodology developed in this dissertation. Many of the constraints driving the mathematical model are somewhat flexible, and sound judgment is required to incorporate them in an effective way. The method also relies on the intuition and experience of the planners to select a promising schedule from the set of optimal production plans produced by the method.

- **Shipyard culture:** The implementation of an automatic planning method is only successful if it is accepted by all involved parties. This poses a potentially difficult task, especially when considering a shipyard with many competing stakeholders, each with their own objectives. Furthermore, some portion of the workforce will inherently resist any new method that alters their way of working, especially if this way of working has been historically successful.

An implementation approach must be designed that is generally accepted and beneficial for all parties to overcome this.

- **Computational power:** The capabilities of the developed methodology are limited by the available computational power. This is especially true for the scheduling of outfitting tasks as days of computational time can be required. However, computation power will also become a limitation for the scheduling of erection and section building as the problem size and complexity is increased. Although computation power does not particularly restrict the capability to generate an initial production plan, it can potentially hinder a dynamic implementation of methodology. This occurs because updates to the production schedule must be frequently re-calculated in such an implementation.

9.3 Recommendations

This section presents some recommendations to both the research community and shipyards. The first set of recommendations describe additional research which could be done to improve the automatic planning method developed by this dissertation.

- **Use simulation to evaluate schedules:** Currently, resource curves and other simple process characteristics are used to evaluate the quality of the production schedules created by the automatic planning method. Alternatively, a discrete event simulation of the shipbuilding process could be used to asses their quality. This would allow the feasibility of each proposed plan to be tested at a much higher level of detail. Simulating the shipbuilding process is not a new concept. Notable past research has focused on the section assembly process (Caprace et al., 2011), the plate prefabrication process (Kaarsemaker and Nienhuis, 2006), the outfitting process (König et al., 2007), and an entire shipyard (Steinhauer, 2011).

- **Adapt for very early stage planning:** The automatic planning methods developed for erection and section building could be optimized for very early stage planning. During this stage, shipyards only have access to a crude general arrangement. Many of the constraints considered in this dissertation do not exist. For example, the installation time of large component cannot be considered since this equipment has not yet been ordered. Task durations and man-hours per section are also typically fixed using crude estimation techniques. Furthermore, the section divisions are still somewhat flexible.

- **Integrate with automatic design tools:** The methodology developed in this dissertation could also be used as a means for evaluating the output of automatic design tools (such as those described in Section 3.5). For example, consider the automatic pipe routing framework of Asmara (2013). This tool uses some rudimentary formulas to calculate the total installation cost of the piping of a main engine room. However, a more detailed cost estimation could be attained by first automatically developing an outfitting plan for the machinery space.

- **Adapt to other shipyards and ship types:** The constraints and objectives used in this dissertation were tailored to the test case ship (a pipelaying ship built at Royal IHC). However, the method was designed to be applicable for other complex ship types built in other locations. To do this, additional constraints must be investigated and implemented. For example, the test case ship used azimuthing thrusters for propulsion. This meant that no constraints related to shaft alignment were included, even though shaft alignment plays a critical role in erection process of ships using fixed propellers.

- **Include engineering and procurement:** The assumption was made in this dissertation that all engineering drawings, steel parts, and components were available at any point in time. As a result, the automatic planning methodology optimized the production schedules without consideration of the engineering and procurement processes. In reality, these two processes can significantly hinder the production of a ship, especially in an extremely time sensitive project. Including these processes in the methodology could improve the accuracy and applicability of the results.

- **Optimize solution methodology:** Little effort was done in this dissertation to optimize the solution techniques used to solve the mathematical models developed for the shipbuilding process. Instead, a feasible solution technique was developed to show that it was possible to find solutions superior to those created manually by shipyard planners in a reasonable computational time. However, the quality of the production schedules resulting from the automatic planning method could be improved by comparing the performance of different algorithms, properly tuning parameters, and testing alternative solution approaches.

The second set of recommendations are directed at any shipyard desiring to someday implement an automatic planning method similar to the one developed in this dissertation. These recommendations would also be useful for any shipyard interested in using any kind of quantitative optimization method to improve their production process. These recommendations stem from some of the major challenges faced while performing this research.

- **Collect as much production data as possible:** The research presented in this dissertation was sometimes hindered by the lack of measured data from the production process. For example, it was necessary to use crude estimation methods to predict the mounting times of outfitting tasks. A more sophisticated approach could have been developed and implemented if the test case shipyard had historically collected mounting time data. Unfortunately, this was not possible due to the lack of data. Complete sets of the following process-related data would have been the most beneficial to this dissertation:

    - Logistics (for components, workers, and equipment)
    - Task durations (broken into sub-tasks where possible)
    - Video recordings of important processes and work areas

- **Fully define and integrate geometry data:** Significant effort was required to integrate the various information sources describing the ship used in the test cases presented in Chapters 4 through 7. This effort often required manual work splicing together difference spreadsheets, databases, word documents, etc. Furthermore, it was not possible to access some geometric data generated internally by subcontractors (such as the routing of some HVAC ducting and cable trays). This data preparation was required because departments often used internally-developed tools to keep track of their own data. Developing an integrated, centralized system linked to a fully defined 3D model of a ship would have removed the need to perform this data integration work.

- **Explicitly define process constraints:** The constraints governing the shipbuilding process were usually described by planners and foremen as inflexible, hard constraints. However, the production schedules used by the shipyard systematically violated some of these constraints. When confronted about these violations, these personnel stated such violations were undesired, but necessary to deliver the ship on time. A thorough investigation into the situations that allow for constraint violation and the degree to which each constraint can be violated would improve the quality of the solutions created by an automatic planning method. Such an investigation might also result in potential improvements to the production and design process.

Appendix A

Erection Sequences of Test Case Ship

This appendix shows two erection sequences from the test case ship presented in Chapter 4. The first sequence was produced by the Erection Planning Method, and the second sequence was created manually by shipyard planners.

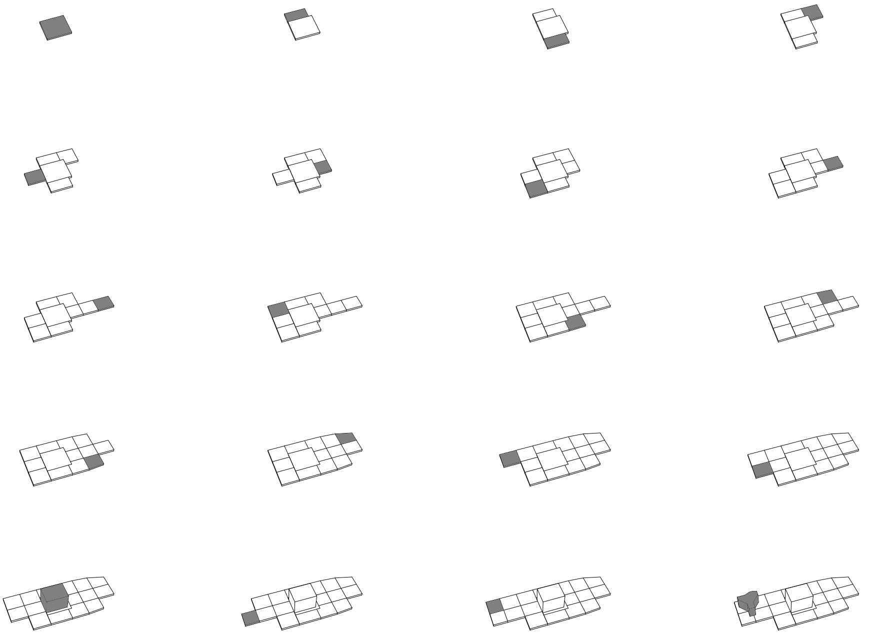

Figure A.1: Erection sequence produced by Erection Planning Method

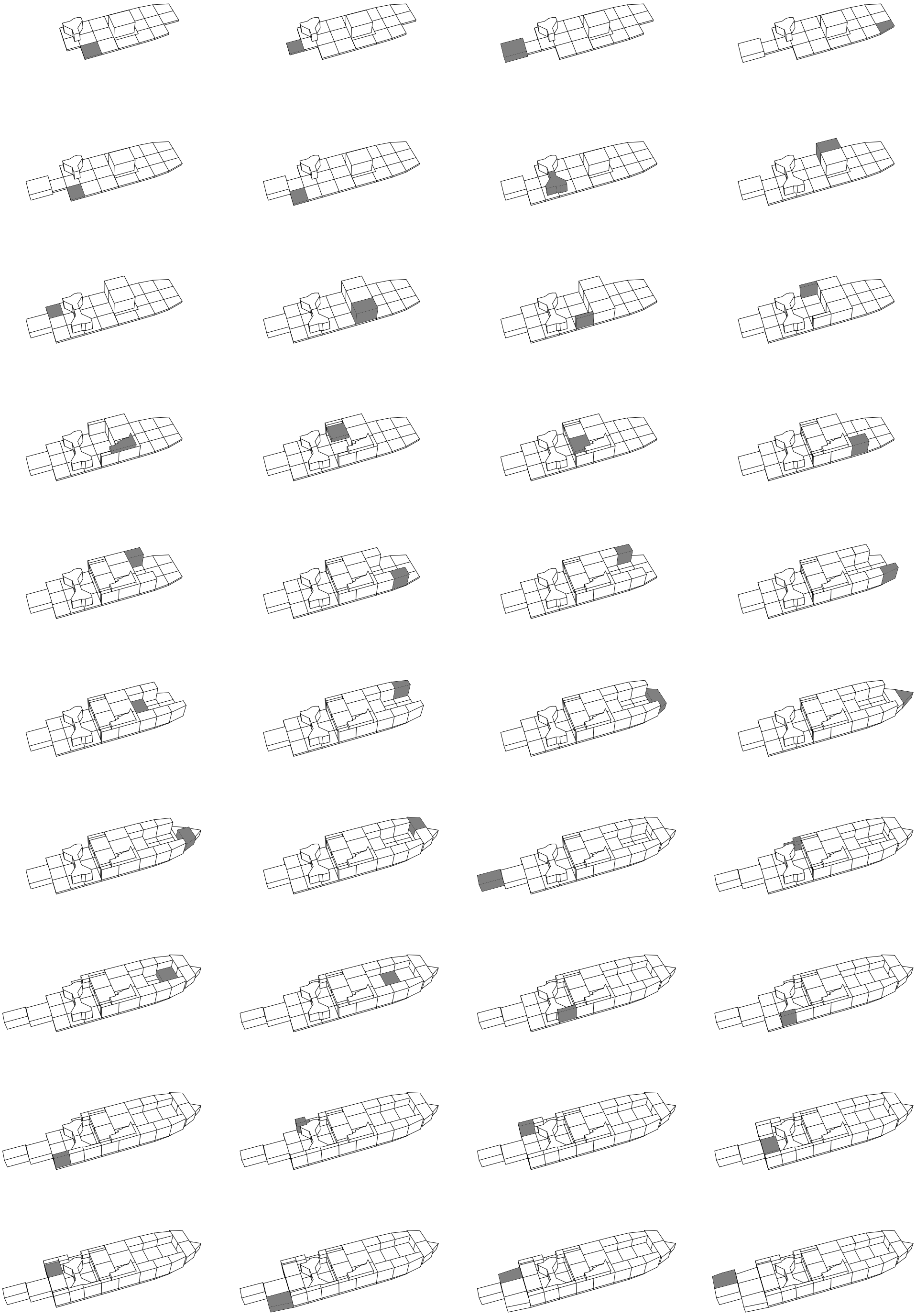

Figure A.1: Erection sequence produced by Erection Planning Method (cont.)

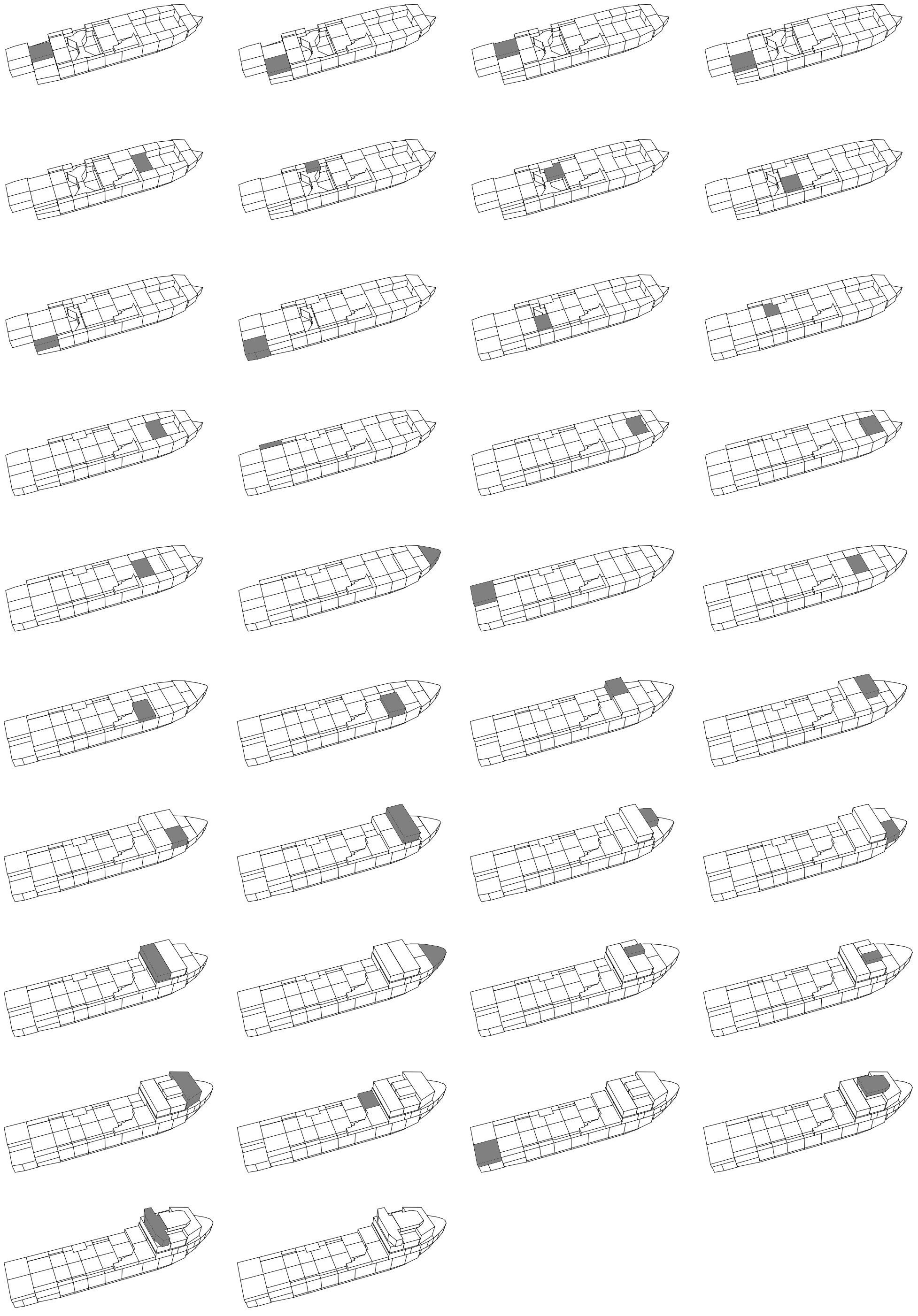

Figure A.1: Erection sequence produced by Erection Planning Method (cont.)

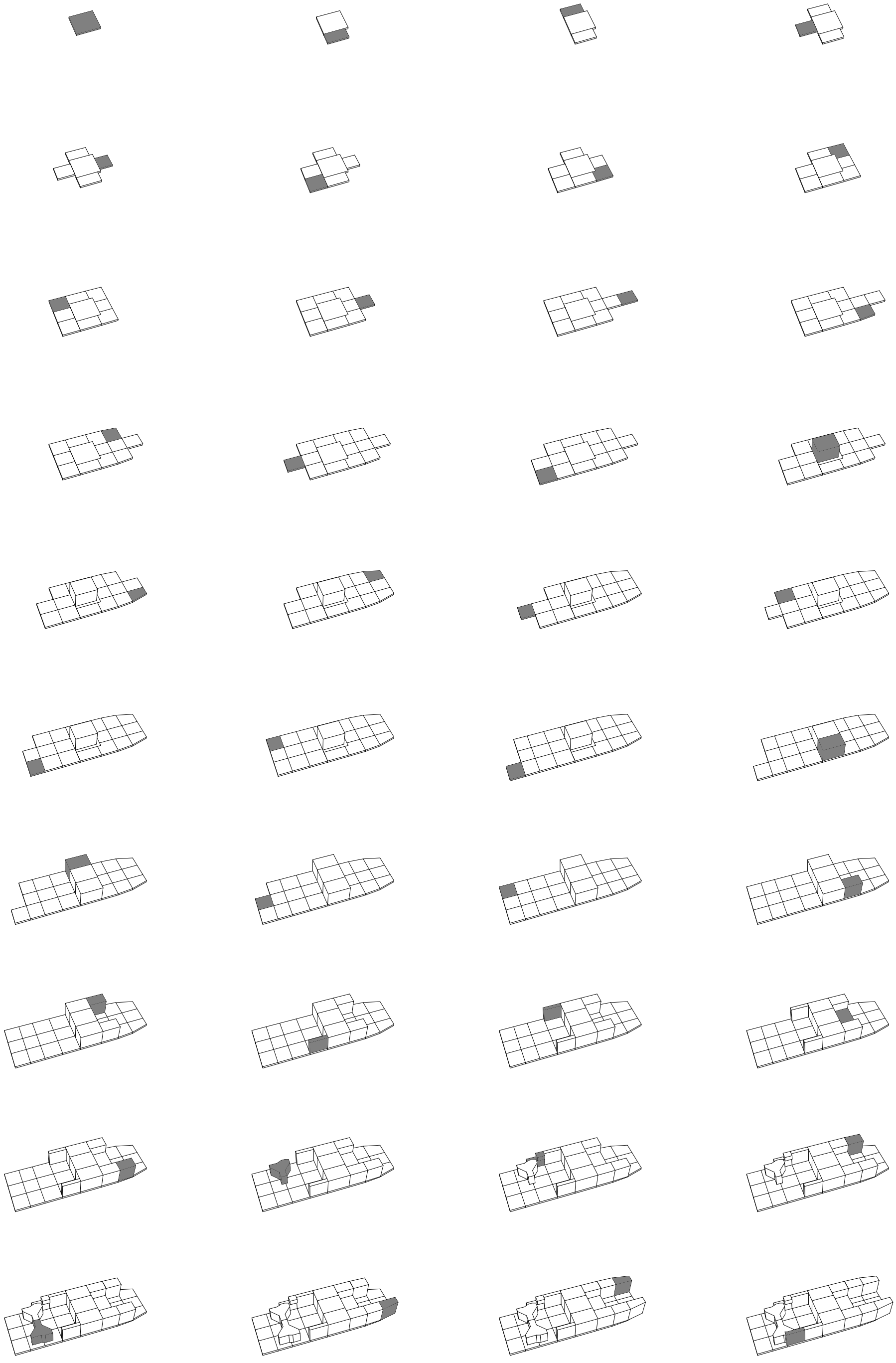

Figure A.2: Erection sequence produced by shipyard planners

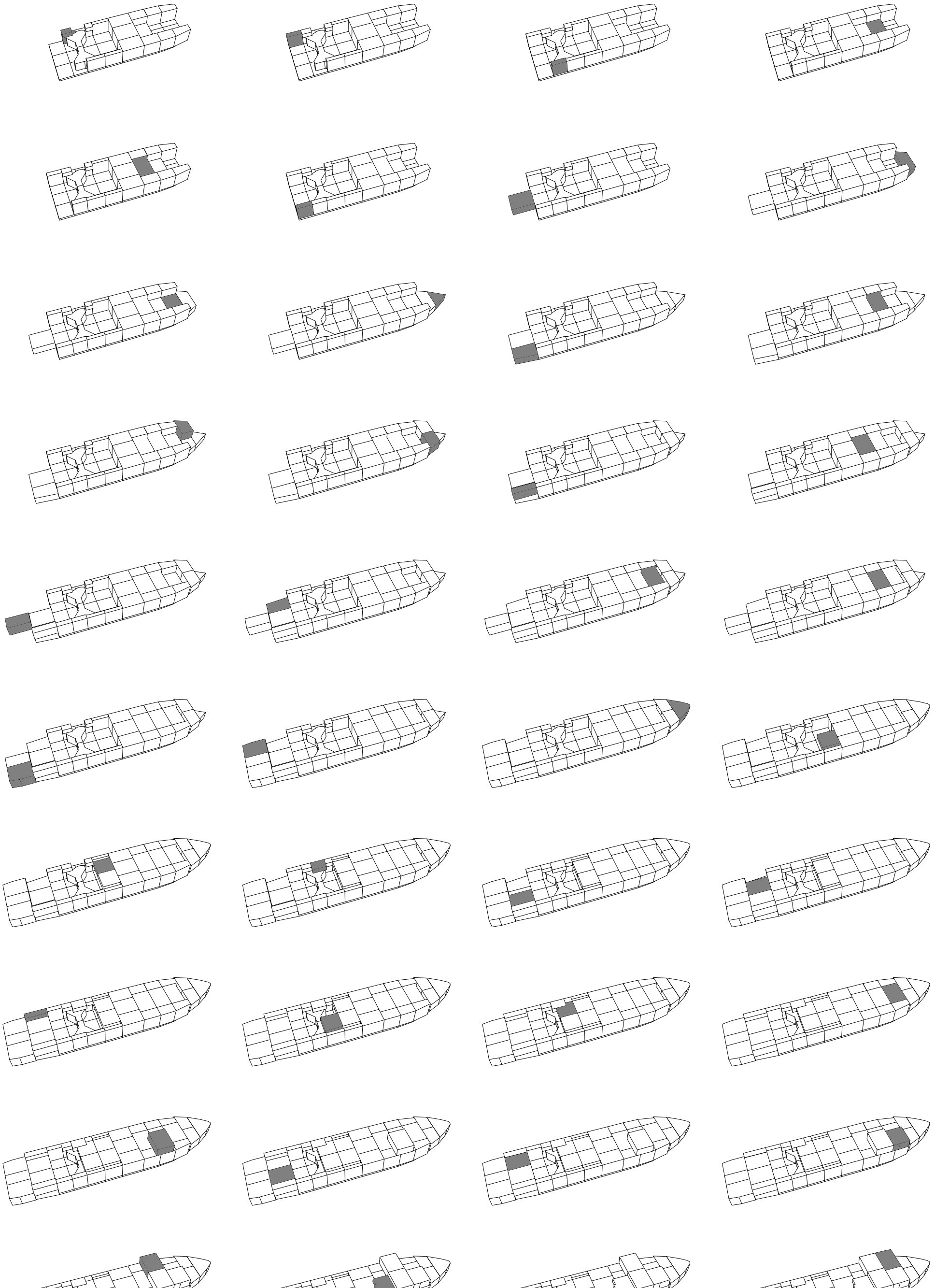

Figure A.2: Erection sequence produced by shipyard planners (cont.)

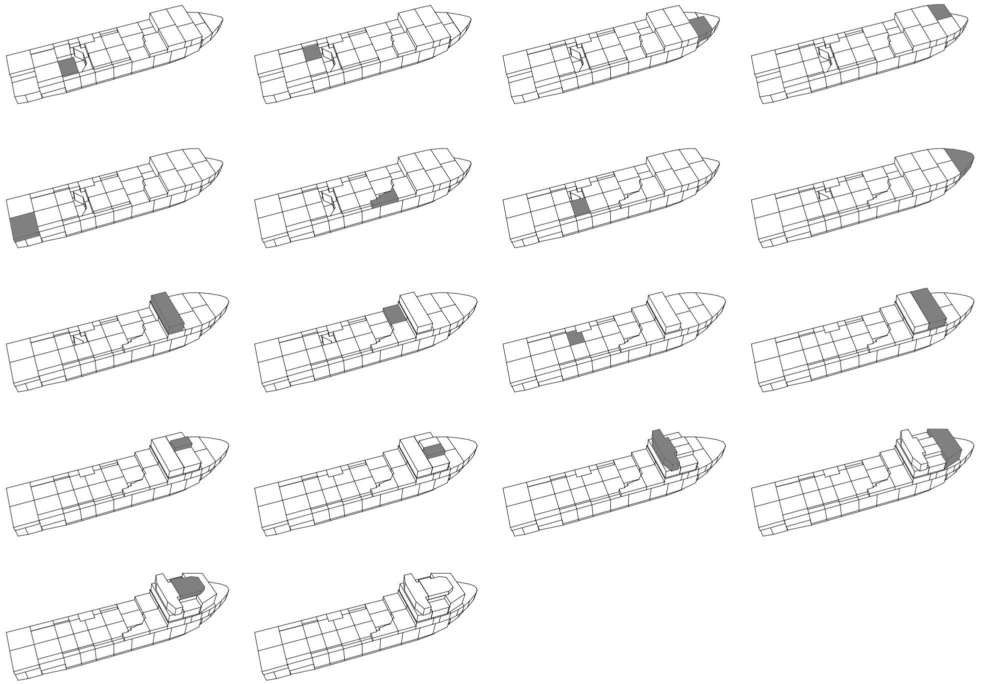

Figure A.2: Erection sequence produced by shipyard planners (cont.)

Appendix B

Description of Participants of Validation Interviews

This appendix provides a description of the personnel interviewed to validate the Erection Planning Method and Section Building Planning Method (see Sections 4.7 and 5.7). Table B.1 describes the participants of the validation of the Erection Planning Method, and Table B.2 describes the participants of the validation of the Section Building Planning Method.

Table B.1: Participants of Erection Planning Method validation

Group	Job description	Company
A	Project planner	Royal IHC
B	Project manager product life cycle	Feadship
B	Retired (formerly managing director)	Scheepswerf Slob
C	Section building and erection planner	Royal IHC
C	Outfit and commissioning planner	Royal IHC
C	Erection manager	Royal IHC
C	Erection foreman	Royal IHC

Table B.2: Participants of Section Building Planning Method validation

Group	Job description	Company
A	Project planner	Royal IHC
B	Project manager product life cycle	Feadship
B	Retired (formerly managing director)	Scheepswerf Slob
D	Section building and erection planner	Royal IHC
D	Outfit and commissioning planner	Royal IHC
D	Section assembly manager	Royal IHC
D	Head work preperation	Royal IHC

References

Adler, D. Genetic algorithms and simulated annealing: a marriage proposal. In *Proceedings of the IEEE International Conference on Neural Networks*, pages 1104–1109. IEEE, San Francisco, 1993. ISBN 0780309995.

Allahverdi, A., Gupta, J. N., and Aldowaisan, T. A review of scheduling research involving setup considerations. *Omega*, 27(2):219–239, 1999. ISSN 0305-0483.

Anagnostopoulos, G. C. and Rabadi, G. A simulated annealing algorithm for the unrelated parallel machine scheduling problem. In *Proceedings of the 5th Biannual World Automation Congress*, volume 14, pages 115–120. IEEE, 2002. ISBN 1889335185.

Asmara, A. *Pipe routing framework for detailed ship design.* VSSD, Delft, 2013.

Bao, J., Wang, Q., and Xu, A. A steerable GA method for block erection of shipbuilding in virtual environment. In *Cooperative Design, Visualization, and Engineering*, pages 286–293. Springer International Publishing, 2014. ISBN 3319108301.

Berghuis, E. and Den Butter, F. A. Labour market effects of international fragmentation of production: evidence from a survey and case studies in the Dutch industry. Report, Tinbergen Institute, 2013.

Berrichi, A., Amodeo, L., Yalaoui, F., Chtelet, E., and Mezghiche, M. Bi-objective optimization algorithms for joint production and maintenance scheduling: application to the parallel machine problem. *Journal of Intelligent Manufacturing*, 20(4):389–400, 2009. ISSN 0956-5515.

Berrichi, A., Yalaoui, F., Amodeo, L., and Mezghiche, M. Bi-objective ant colony optimization approach to optimize production and maintenance scheduling. *Computers & Operations Research*, 37(9):1584–1596, 2010. ISSN 0305-0548.

Blazewicz, J., Domschke, W., and Pesch, E. The job shop scheduling problem: conventional and new solution techniques. *European Journal of Operational Research*, 93(1):1–33, 1996. ISSN 0377-2217.

Boctor, F. F. Resource-constrained project scheduling by simulated annealing. *International Journal of Production Research*, 34(8):2335–2351, 1996. ISSN 0020-7543.

Brucker, P., Drexl, A., Mhring, R., Neumann, K., and Pesch, E. Resource-constrained project scheduling: notation, classification, models, and methods. *European Journal of Operational Research*, 112(1):3–41, 1999. ISSN 0377-2217.

Caprace, J. D., Bair, F., and Rigo, P. Multi-criterion scantling optimisation of passenger ships. In *Proceedings of the 9th International Conference on Computer Applications and Information Technology in the Maritime Industries*. 2010.

Caprace, J. D., Trevisani Da Silva, C., Rigo, P., and Martins Pires, F. C. Discrete event production simulation and optimisation of ship block erection process. In Bertram, V., editor, *Proceedings of the 10th the International Conference on Computer Applications and Information Technology in the Maritime Industries*, pages 271–282. Berlin, 2011.

Carrasquilla, J. Identifying relationships amoung electrical outfitting activities. Report, Integraal Samenwerken, 2013.

CESA. Annual report 2010-2011. Report, 2011.

Chen, P. H. and Shahandashti, S. M. Hybrid of genetic algorithm and simulated annealing for multiple project scheduling with multiple resource constraints. *Automation in Construction*, 18(4):434–443, 2009. ISSN 0926-5805.

Cheng, C. Y., Chen, T. L., Wang, L. C., and Chen, Y. Y. A genetic algorithm for the multi-stage and parallel-machine scheduling problem with job splitting: a case study for the solar cell industry. *International Journal of Production Research*, 51 (16):4755–4777, 2013. ISSN 0020-7543.

Cheng, T. and Sin, C. A state-of-the-art review of parallel-machine scheduling research. *European Journal of Operational Research*, 47(3):271–292, 1990. ISSN 0377-2217.

Cho, K. K., Lee, S. H., and Chung, D. S. An automatic process-planning system for block assembly in shipbuilding. *CIRP Annals-Manufacturing Technology*, 45(1): 41–44, 1996. ISSN 0007-8506.

Cho, K. K., Sun, J. G., and Oh, J. S. An automated welding operation planning system for block assembly in shipbuilding. *International Journal of Production Economics*, 60:203–209, 1999. ISSN 0925-5273.

Colthoff, R. *Schedule Generation for Section Construction Activities*. MSc thesis, 2009.

Conference Board. International comparisons of hourly compensation costs in manufacturing, 2013. Report, The Conference Board Inc., 2014.

Damci, A. and Polat, G. Impacts of different objective functions on resource leveling in construction projects: a case study. *Journal of Civil Engineering and Management*, 20(4):537–547, 2014. ISSN 1392-3730.

Deb, K. and Karthik, S. Dynamic multi-objective optimization and decision-making using modified NSGA-II: a case study on hydro-thermal power scheduling. In *Evolutionary Multi-Criterion Optimization*, pages 803–817. Springer, Berlin Heidelberg, 2007. ISBN 3540709274.

Deb, K., Pratap, A., Agarwal, S., and Meyarivan, T. A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation*, 6(2):182–197, 2002. ISSN 1089-778X.

Demeulemeester, E. Minimizing resource availability costs in time-limited project networks. *Management Science*, 41(10):1590–1598, 1995. ISSN 0025-1909.

Drexl, A. and Kimms, A. Optimization guided lower and upper bounds for the resource investment problem. *Journal of the Operational Research Society*, 52(3): 340–351, 2001. ISSN 0160-5682.

ECORYS. Study on competitiveness of the European shipbuilding industry. Report, 2009.

Eiben, A. E. and Smit, S. K. Parameter tuning for configuring and analyzing evolutionary algorithms. *Swarm and Evolutionary Computation*, 1(1):19–31, 2011. ISSN 2210-6502.

Eyres, D. J. and Bruce, G. J. *Ship Construction*. Butterworth-Heinemann, 2012. ISBN 008097239X.

Framinan, J. and Ruiz, R. Architecture of manufacturing scheduling systems: literature review and an integrated proposal. *European Journal of Operational Research*, pages 237–246, 2010.

Garrido, A., Arangu, M., and Onaindia, E. A constraint programming formulation for planning: from plan scheduling to plan generation. *Journal of Scheduling*, 12 (3):227–256, 2009.

Grajcar, M. Genetic list scheduling algorithm for scheduling and allocation on a loosely coupled heterogeneous multiprocessor system. In *Proceedings of the Design Automation Conference*, pages 280–285. IEEE, New Orleans, 1999.

Granger, N. Report of the HR workshop: demographic change & skills requirements in the European shipbuilding & ship repair industry. Report, CESA, 2008.

Graves, R. J. and McGinnis, L. F. The outfit planning problem: Production planning in shipbuilding. *Naval Research Logistics Quarterly*, 29(2):357–384, 1982. ISSN 1931-9193.

Gregory, C. *Improving the Pre-Outfit Strategy for a Shipbuilding Project: Generation of a More Detailed Outfit Schedule in the Pre-contract Phase*. MSc thesis, 2015.

Grimmelius, H., Nuur, N., and van Hees, M. Knowledge-based assembly of dynamic simulation models. In *Proceedings of the 8th International Conference on Computer and IT Applications in the Maritime Industries*. Budapest, 2009.

Hansen, P. Bicriterion path problems. In *Proceedings of the Multiple Criteria Decision Making Theory and Application*, pages 109–127. Springer, 1980. ISBN 3540099638.

Hartmann, S. and Briskorn, D. A survey of variants and extensions of the resource-constrained project scheduling problem. *European Journal of Operational Research*, 207(1):1–14, 2010. ISSN 0377-2217.

Hegazy, T., Shabeeb, A. K., Elbeltagi, E., and Cheema, T. Algorithm for scheduling with multiskilled constrained resources. *Journal of Construction Engineering and Management*, 126(6):414–421, 2000. ISSN 0733-9364.

Heimerl, C. and Kolisch, R. Scheduling and staffing multiple projects with a multi-skilled workforce. *OR Spectrum*, 32(2):343–368, 2010. ISSN 0171-6468.

Hoitomt, D., Luh, P., Max, E., and Pattipati, K. Scheduling jobs with simple precedence constraints on parallel machines. *IEEE Control Systems Magazine*, pages 34–40, 1990.

Holte, E. and Moen, Ø. Successful maritime clusters: key drivers and criteria. Report IGLO-MP 2020, Norwegian University of Science and Technology, 2010.

Hsu, C. C. and Kim, D. S. A new heuristic for the multi-mode resource investment problem. *Journal of the Operational Research Society*, 56(4):406–413, 2005. ISSN 0160-5682.

Hu, X., Bao, J. S., and Jin, Y. Minimizing makespan on parallel machines with precedence constraints and machine eligibility restrictions. *International Journal of Production Research*, 48(6):1639–1651, 2010.

Hurink, J. and Knust, S. List scheduling in a parallel machine environment with precedence constraints and setup times. *Operations Research Letters*, pages 231–239, 2001.

IKEI. Comprehensive sectoral analysis of emerging competences and economic activities in the European Union. Report, DG Employment, Social Affairs and Equal Opportunities, 2009.

Jinsong, B., Xiaofeng, H., and Ye, J. A genetic algorithm for minimizing makespan of block erection in shipbuilding. *Journal of Manufacturing Technology Management*, 20(4):500–512, 2009.

Kaarsemaker, J. and Nienhuis, U. Simulation of a maritime pre-fabrication process. In *Proceedings of the 5th International Conference on Computer Applications and Information Technology in the Maritime Industries*, pages 419–431. Delft, 2006.

Kaibel, V. and Peinhardt, M. On the bottleneck shortest path problem. Technical report, DFG Research Center, 2006.

Kim, H., Kang, J., and Park, S. Scheduling of shipyard block assembly process using constraint satisfaction problem. *Asia Pacific Management Review*, 7(1): 119–138, 2002.

Koenig, P. C., Narita, H., and Baba, K. Lean production in the Japanese shipbuilding industry. *Journal of Ship Production*, 18(3):167–174, 2002. ISSN 8756-1417.

Koh, S., Logendran, R., and Choi, D. Spatial scheduling for shape-changing mega-blocks in a shipbuilding company. *International Journal of Production Research*, 49(23):7135–7149, 2011.

Kolic, D., Fafandjel, N., and Calic, B. Determining how to apply the design for production concept in shipyards through risk analysis. *Engineering Review*, 30(1): 63–72, 2010. ISSN 1330-9587.

Kolisch, R. Efficient priority rules for the resource-constrained project scheduling problem. *Journal of Operations Management*, pages 179–192, 1996.

Kondayya, D. and Krishna, A. G. An integrated evolutionary approach for modelling and optimisation of CNC end milling process. *International Journal of Computer Integrated Manufacturing*, 25(11):1069–1084, 2012. ISSN 0951-192X.

König, M., Beißert, U., Steinhauer, D., and Bargstadt, H. J. Constraint-based simulation of outfitting processes in shipbuilding and civil engineering. In *Proceedings of the 6th EUROSIM Congress on Modeling and Simulation*. Ljubljana, 2007.

Koomey, J., Berard, S., Sanchez, M., and Wong, H. Implications of historical trends in the electrical efficiency of computing. *IEEE Annals of the History of Computing*, pages 46–54, 2011.

Kuster, J. and Jannach, D. Handling airport ground processes based on resource-constrained project scheduling. In *Advances in Applied Artificial Intelligence*, pages 166–176. Springer, 2006. ISBN 3540354530.

Larranaga, P., Kuijpers, C., Murga, R., and Yurramendi, Y. Learning Bayesian network structures by searching for best ordering with genetic algorithms. *Transactions on Systems, Man, and Cybernetics*, 26(4):487–493, 1996.

LeaderSHIP 2015. Defining the future of the European shipbuilding and shiprepair industry. Report, European Commission, 2003.

LeaderSHIP 2020. The sea: new opportunities for the future. Report, European Commision, 2013.

Lee, J. K., Lee, K. J., Park, H. K., Hong, J. S., and Lee, J. S. Developing scheduling systems for Daewoo Shipbuilding: DAS project. *European Journal of Operational Research*, 97(2):380–395, 1997.

Li, Q., Gong, J., Fung, R. Y., and Tang, J. Multi-objective optimal cross-training configuration models for an assembly cell using non-dominated sorting genetic algorithm-II. *International Journal of Computer Integrated Manufacturing*, 25 (11):981–995, 2012. ISSN 0951-192X.

Linyi, D. and Yan, L. A particle swarm optimization for resource-constrained project scheduling. In *Proceedings of the International Conference on Computational Intelligence and Security*, pages 1010–1014. IEEE Computer Society, Harbin, 2007.

Liu, S. S. and Wang, C. J. Optimizing linear project scheduling with multi-skilled crews. *Automation in Construction*, 24:16–23, 2012. ISSN 0926-5805.

Liu, Z., Chua, D. K. H., and Yeoh, K. W. Aggregate production planning for shipbuilding with variation-inventory trade-offs. *International Journal of Production Research*, 49(20):6249–6272, 2011. ISSN 0020-7543.

Luh, P., Hoitomt, D., Max, E., and Pattipati, K. Schedule generation and reconfiguration for parallel machines. *IEEE Transactions on Robotics and Automation*, pages 687–696, 1990.

Maffioli, P., Daidola, J. C., and Olivier, J. Competitive shipbuilding practices. *SNAME Transactions*, 2001.

Mao, K., Pan, Q., Pang, X., and Chai, T. A novel Lagrangian relaxation approach for a hybrid flowshop scheduling problem in the steelmaking-continuous casting process. *European Journal of Operational Research*, 236(1):51–60, 2014. ISSN 0377-2217.

Martins, E. Q. V. On a multicriteria shortest path problem. *European Journal of Operational Research*, 16(2):236–245, 1984. ISSN 0377-2217.

Meijer, K. *Erection Scheduling Support Tool*. MSc thesis, 2008.

Meijer, K., Pruyn, J., and Klooster, J. Erection scheduling support tool. In *Proceedings of the 8th International Conference on Computer and IT Applications in the Maritime Industries*, pages 326–332. Budapest, 2009.

Meyer Werft. Meyer werft: Production engineering, 2015. URL `http://www.meyerwerft.de/en/meyerwerft_de/werft/produktionstechnik/produktionstechnik.jsp`.

Mickeviciene, R. Global shipbuilding competition: Trends and challenges for Europe. In *The Economic Geography of Globalization*, pages 201–222. InTech, 2011.

Möhring, R. H. Minimizing costs of resource requirements in project networks subject to a fixed completion time. *Operations Research*, 32(1):89–120, 1984. ISSN 0030-364X.

Möhring, R. H., Skutella, M., and Stork, F. Scheduling with and/or precedence constraints. *SIAM Journal on Computing*, 33(2):393–415, 2004. ISSN 0097-5397.

Mönch, L., Fowler, J. W., Dauzre-Prs, S., Mason, S. J., and Rose, O. A survey of problems, solution techniques, and future challenges in scheduling semiconductor manufacturing operations. *Journal of Scheduling*, 14(6):583–599, 2011. ISSN 1094-6136.

Mourtzis, D. An integrated system for managing ship repair operations. *International Journal of Computer Integrated Manufacturing*, 18(8):721–733, 2005. ISSN 0951-192X.

Müller, T. Managing cyclical change in the European shipbuilding and ship repair industries. Report, European Foundation for the Improvement of Living and Working Conditions, 2007.

Murugan, P., Kannan, S., and Baskar, S. NSGA-II algorithm for multi-objective generation expansion planning problem. *Electric Power Systems Research*, 79(4): 622–628, 2009. ISSN 0378-7796.

Nallikari, M. Multiskilled work teams at Finnish shipyards. *Journal of Ship Production*, 11(4):239–244, 1995. ISSN 8756-1417.

Neumann, K. and Zimmermann, J. Resource levelling for projects with schedule-dependent time windows. *European Journal of Operational Research*, 117 (3):591–605, 1999. ISSN 0377-2217.

Olsson, R. Subcontract coordination in construction. *International Journal of Production Economics*, pages 503–509, 1998.

Patterson, J. Project scheduling: the effects of problem structure on heuristic performance. *Naval Research Logistics*, page 95123, 1976.

Pezzella, F., Morganti, G., and Ciaschetti, G. A genetic algorithm for the flexible job-shop scheduling problem. *Computers & Operations Research*, 35(10): 3202–3212, 2008. ISSN 0305-0548.

Phanden, R. K., Jain, A., and Verma, R. Integration of process planning and scheduling: a state-of-the-art review. *International Journal of Computer Integrated Manufacturing*, 24(6):517–534, 2011. ISSN 0951-192X.

Pratap, S., Kumar B, M., Saxena, D., and Tiwari, M. Integrated scheduling of rake and stockyard management with ship berthing: a block based evolutionary algorithm. *International Journal of Production Research*, pages 1–23, 2015a. ISSN 0020-7543.

Pratap, S., Nayak, A., Cheikhrouhou, N., and Tiwari, M. K. Decision support system for discrete robust berth allocation. *IFAC-PapersOnLine*, 48(3):875–880, 2015b. ISSN 2405-8963.

Qin, Y. F. and Xu, Z. G. Assembly process planning using a multi-objective optimization method. In *Proceedings of the International Conference on Mechatronics and Automation*, pages 593–598. Harbin, 2007.

Ramachandra, G. and Elmaghraby, S. Sequencing precedence-related jobs on two machines to minimize the weighted completion time. *International Journal of Production Economics*, pages 44–58, 2006.

Rigo, P. and Caprace, J. D. Optimisation of ship structures. In Guedes Soares, C., editor, *Marine Technology and Engineering*, pages 925–944. Taylor & Francis Ltd, London, 2011.

Rigo, P., Zanic, V., Ehlers, S., and Andric, J. Design of innovative ship concepts using an integrated decision support system for ship production and operation. *Journal of Naval Architecture and Shipbuilding Industry*, 61(4):367–381, 2010.

Rigterink, D., Collette, M., and Singer, D. J. A method for comparing panel complexity to traditional material and production cost estimating techniques. *Ocean Engineering*, 70:61–71, 2013. ISSN 0029-8018.

Roh, M. I. and Lee, K. Y. Generation of production material information for a building block and simulation of block erection for process planning and scheduling in shipbuilding. *International Journal of Production Research*, 45(20): 4653–4683, 2007. ISSN 0020-7543.

Rose, C. and Coenen, J. Current state of automated design tools for increasing availability of data early in the ship design process. In *Proceedings of the International Conference of Maritime Technology*. Glasgow, 2014.

Rose, C. and Coenen, J. Automatically determining the latest possible equipment installation times for shipbuilding. In *Proceedings from the World Maritime Technology Conference*. Society of Naval Architects and Marine Engineers, Providence, 2015a.

Rose, C. and Coenen, J. Comparing four metaheuristics for solving a constraint satisfaction problem for ship outfitting scheduling. *International Journal of Production Research*, 53(19):5782–5796, 2015b.

Rose, C. and Coenen, J. Determining ship outfitting task priorities using latest finish time distributions. In *Proceedings of the 17th International Conference for Computer Applications in Shipbuilding*. Royal Institution of Naval Architects, Bremen, 2015c.

Rose, C. and Coenen, J. Automatic generation of a section erection planning for European shipyards building complex ships. *Journal of Manufacturing Technology Management*, 27(4):483–501, 2016a.

Rose, C. and Coenen, J. Automatic generation of a section building planning for constructing complex ships in European shipyards. *International Journal of Production Research*, 2016b.

Rose, C. and Coenen, J. Automatic generation of a detailed outfitting planning and determining the effect of multi-skilled mounting teams. In *Proceedings of the 14th International Conference on Manufacturing Research*. IOS Press, Loughborough, 2016c.

Rose, C., Coenen, J., and Hopman, H. Definition of ship outfitting as resource availability cost problem and development and testing of a heuristic solution technique. *Journal of Ship Production and Design*, 32(3), 2016.

Rubesa, R., Fafandjel, N., and Kolic, D. Procedure for estimating the effectiveness of modular outfitting. *Engineering Review*, 31(1):55–62, 2011.

Sadeghi, J., Sadeghi, S., and Niaki, S. T. A hybrid vendor managed inventory and redundancy allocation optimization problem in supply chain management: an NSGA-II with tuned parameters. *Computers & Operations Research*, 41:53–64, 2014. ISSN 0305-0548.

Safaei, N., Banjevic, D., and Jardine, A. Multi-threaded simulated annealing for a bi-objective maintenance scheduling problem. *International Journal of Production Research*, 50(1):63–80, 2011.

Sakalauskas, L. and Felinskas, G. Optimization of resource constrained project schedules by genetic algorithm based on the job priority list. *Information Technology and Control*, 35(4):412–418, 2006.

Schank, J., Pung, H., Lee, G., Arena, M., and Birkler, J. Outsourcing and outfitting practices: implications for the ministry of defence shipbuilding programmes. Report, RAND Corporation, 2005.

Schutt, A., Feydy, T., Stuckey, P., and Wallace, M. Solving RCPSP/max by lazy clause generation. *Journal of Scheduling*, pages 273–289, 2013.

SEA Europe. Supplying, building, & maintaining the future. Report, 2014.

Seepersad, C. C., Pedersen, K., Emblemsvag, J., Bailey, R., Allen, J. K., and Mistree, F. The validation square: how does one verify and validate a design method. Report, 2005.

Seo, Y., Sheen, D., and Kim, T. Block assembly planning in shipbuilding using case-based reasoning. *Expert Systems with Applications*, 32(1):245–253, 2007.

Sha, D. Y. and Hsu, C. Y. A hybrid particle swarm optimization for job shop scheduling problem. *Computers & Industrial Engineering*, (51):791–808, 2006.

Shibuilder's Association of Japan. Shipbuilding statistics. Report, 2015.

Steinhauer, D. The simulation toolkit shipbuilding (STS) 10 years of cooperative development and interbranch applications. In *Proceedings of the 10th International Conference on Computer and IT Applications in the Maritime Industries*, pages 453–465. Berlin, 2011.

Stinson, J., Davis, E., and Khumawala, B. Multiple resource-constrained scheduling using branch and bound. *AIIE Transactions*, pages 252–259, 1978.

Storch, R., Hammon, C., Bunch, H., and Moore, R. *Ship Production.* Society of Naval Architechts and Marine Engineers, 2nd edition, 1995.

Storch, R. L. Improving flow to achieve lean manufacturing in shipbuilding. *Production Planning & Control*, 10(2):127–137, 1999. ISSN 0953-7287.

Stravinski, D. Multiskilled, self-managing work teams in a zone-construction environment. *Journal of Ship Production*, 5(1):36–53, 1989. ISSN 8756-1417.

't Hart, P. and Schotte, D. Demographic change and skill requirements in the shipbuilding industry & ship repair industry. HR research study, Koers & Vaart, 2008.

Tam, V. W., Shen, L., and Kong, J. S. Impacts of multi-layer chain subcontracting on project management performance. *International Journal of Project Management*, 29(1):108–116, 2011. ISSN 0263-7863.

Ulusoy, G. and Özdamar, L. A constraint-based perspective in resource constrained project scheduling. *International Journal of Production Research*, pages 693–705, 1994.

van Es, G. F. and de Vos, P. System design as a decisive step in engineering naval capability. In *Proceedings of the 11th International Naval Engineeing Conference and Exibition*. Edinburgh, UK, 2012.

van Oers, B. *A packing approach for the early design of service vessels*. VSSD, Delft, 2011.

van Oers, B. and Hopman, H. A 3D packing approach for the early stage configuration design of ships. In *Proceedings of the 10th International Naval Engineering Conference*. 2010.

Varadharajan, T. and Rajendran, C. A multi-objective simulated-annealing algorithm for scheduling in flowshops to minimize the makespan and total flowtime of jobs. *European Journal of Operational Research*, 167(3):772–795, 2005. ISSN 0377-2217.

Vilcot, G. and Billaut, J. C. A tabu search and a genetic algorithm for solving a bicriteria general job shop scheduling problem. *European Journal of Operational Research*, 190(2):398–411, 2008. ISSN 0377-2217.

Vlaar, W. *Improving the Applicability of a Planning Tool for Shipbuilding Projects*. MSc thesis, 2010.

Wang, B., Yang, X., and Li, Q. Genetic simulated-annealing algorithm for robust job shop scheduling. In *Fuzzy Information and Engineering*. Chongqing, 2009.

Wei, Y. *Automatic generation of assembly sequence for the planning of outfitting process in shipbuilding*. VSSD, Delft, 2012. ISBN 978-90-6562-295-2.

Wei, Y. and Nienhuis, U. Automatic generation of assembly sequence for the planning of outfitting processes in shipbuilding. *Journal of Ship Production and Design*, 28(2):49–59, 2012. ISSN 2158-2866.

Wei, Y., Nienhuis, U., and Moredo, E. Two approaches to scheduling outfitting processes in shipbuilding. *Journal of Ship Production*, 26(1):20–28, 2010. ISSN 2158-2866.

Wongwai, N. and Malaikrisanachalee, S. Augmented heuristic algorithm for multi-skilled resource scheduling. *Automation in Construction*, 20(4):429–445, 2011. ISSN 0926-5805.

Yamashita, D. S., Armentano, V. A., and Laguna, M. Robust optimization models for project scheduling with resource availability cost. *Journal of Scheduling*, 10(1): 67–76, 2007. ISSN 1094-6136.

Zhang, H., Li, X., Li, H., and Huang, F. Particle swarm optimization-based schemes for resource-constrained project scheduling. *Automation in Construction*, pages 393–404, 2005.

Zheng, J., Jiang, Z., Chen, Q., and Liu, Q. Spacial scheduling algorithm minimizing makespan at block assembly shop in shipbuilding. *International Journal of Production Research*, 49(8):2351–2371, 2011.

Zheng, J., Jiang, Z., and Chen, Q. Block spatial scheduling modelling and application in shipbuilding. *International Journal of Production Research*, 50(10): 2744–2756, 2012.

Zhuo, L., Huat, D., and Wee, K. Scheduling dynamic block assembly in shipbuilding through hybrid simulation and spatial optimisation. *International Journal of Production Research*, 50(20):5986–6004, 2012.

Ziarnetzky, T. and Mönch, L. Incorporating engineering process improvement activities into production planning formulations using a large-scale wafer fab model. *International Journal of Production Research*, pages 1–20, 2016. ISSN 0020-7543.

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Curriculum Vitae

Christopher Rose was born on August 3, 1988 in Berlin, Germany. From 2007 to 2011, he studied at Webb Institute and received a BSc in Naval Architecture and Marine Engineering. He obtained a MSc in Maritime Technology from the Delft University of Technology in 2013, following the Ship Design, Production, and Operation track. His graduation project, *Analysis and Optimization of a Machined Steel Kit Manufacturing Process*, examined the part fabrication process of IHC Metalix, a business unit of the Royal IHC shipbuilding group.

In 2013, Christopher started working as a PhD candidate at the Delft University of Technology. His research, presented in this dissertation, was part of the Integraal Samenwerken program. This effort was designed to strengthen the competitiveness of the Dutch shipbuilding industry through supporting research. The initial goal of his project was to improve the outfitting process, but the scope was expanded to also include section building and erection. During his research, he worked closely with the Krimpen aan de IJssel shipyard of the Royal IHC shipbuilding group to link his research with the actual shipbuilding process of a modern European Shipyard.

In addition to his research, Christopher was also heavily involved with educational tasks. He worked as a teaching assistant for *MT727 Shipyard Process, Simulation, and Strategy* and served as the manager and lecturer for *MTM1418 Advanced Ship Production Simulation.* Furthermore, he supervised a total of 3 MSc thesis and 8 BSc thesis students on topics including modularization, man-hour prediction, simulation, and maintenance planning optimization.

Publications

Rose, C. and Coenen, J. Current state of automated design tools for increasing availability of data early in the ship design process. In *Proceedings of the International Conference of Maritime Technology*. Glasgow, 2014.

Rose, C. and Coenen, J. Automatically determining the latest possible equipment installation times for shipbuilding. In *Proceedings from the World Maritime Technology Conference*. Society of Naval Architects and Marine Engineers, Providence, 2015a.

Rose, C. and Coenen, J. Comparing four metaheuristics for solving a constraint satisfaction problem for ship outfitting scheduling. *International Journal of Production Research*, 53(19):5782–5796, 2015b.

Rose, C. and Coenen, J. Determining ship outfitting task priorities using latest finish time distributions. In *Proceedings of the 17th International Conference for Computer Applications in Shipbuilding*. Royal Institution of Naval Architects, Bremen, 2015c.

Rose, C. and Coenen, J. Automatic generation of a section erection planning for European shipyards building complex ships. *Journal of Manufacturing Technology Management*, 27(4):483–501, 2016a.

Rose, C. and Coenen, J. Automatic generation of a section building planning for constructing complex ships in European shipyards. *International Journal of Production Research*, 2016b.

Rose, C. and Coenen, J. Automatic generation of a detailed outfitting planning and determining the effect of multi-skilled mounting teams. In *Proceedings of the 14th International Conference on Manufacturing Research*. IOS Press, Loughborough, 2016c.

Rose, C., Coenen, J., and Hopman, H. Definition of ship outfitting as resource availability cost problem and development and testing of a heuristic solution technique. *Journal of Ship Production and Design*, 32(3), 2016.