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Automatic generation of a section building planning for constructing complex ships in European shipyards

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Efficient planning of the section building process is important for European shipyards since delays in this process can disrupt the on-time delivery of a ship. Automatically generating production schedules of the section building process can result in higher quality schedules compared to those created manually. Recently, the production processes of European shipyards have shifted to focus heavily on outsourcing and outfitting, yet existing automatic planning methods for section building fail to sufficiently consider these factors. This paper develops a mathematical model of the section building process which includes the effects of outfitting and outsourcing. The objective of this model is to simultaneously minimise the fluctuations in workload and the number of outsourced man-hours. The mathematical model was solved by implementing the non-dominated sorting generic algorithm-II (NSGA-II) using a custom heuristic as the fitness function. Due to the multi-objective nature of the problem definition and solution approach, a Pareto front of optimal solutions is created instead of a single, best solution. A test case showed that gains in both objectives are achievable compared to the planning developed manually. Implementing the Section Building Planning methodology developed in this paper could potentially improve the efficiency and controllability of the overall shipbuilding process.

Keywords: production planning; optimisation; genetic algorithms; scheduling; outsourcing; shipbuilding

1. Introduction

In the past decade, the order portfolios of European shipyards have shifted so that these shipyards now almost exclusively build complex ships, such as cruise ships, offshore vessels, yachts and dredgers (SEA Europe 2012). Complex ships differ from simple, cargo ships because they are densely packed with components (e.g. equipment, piping, ducting and cabling). The installation of these components is referred to as outfitting. The level of outfitting required for complex ships poses a significant challenge to European shipyards since a highly skilled workforce is required to install many of these systems. This challenge, coupled with the fact that tough labour policies in many European countries make it costly to adjust the size of a shipyard's permanent workforce (Schank et al. 2005), has led many European shipyards to heavily incorporate outsourcing in their production process. Shipyards routinely outsource the installation of entire systems as well as significant portions of the required steelwork.

Even though the workload of European shipyards has recently shifted to place an increasingly large emphasis on outfitting and outsourcing, the production planning of these shipyards is still very much centred around the steel-related portion of the construction process. The major production milestones of a shipbuilding project (keelaying, launching and delivery) are generally set during contract signing. The shipyard uses these milestones as a basis for planning the section erection process of a ship (Meijer, Pruyn, and Klooster 2009). Erection is the process of combining a ship's steel sections together on the slipway/drydock to form the ship's hull. The production plans of section erection are referred to as the Section Erection Planning. Because the erection process is often a bottleneck for European shipyards (Krause et al. 2004), the erection process generally limits the shipyard's throughput. Furthermore, it is difficult (if not impossible) for shipyards to increase their erection capacity through outsourcing.

The Section Erection Planning 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 Planning. The Section Building Planning must be designed in such a way that each section is ready to be erected at the time indicated in the Section Erection Planning. The Section Building Planning indicates when each section is assembled as well as which sections are built on-site and which sections are outsourced. This planning also sets the time period for which the section is available for pre-outfitting. Pre-outfitting is the process of installing outfitting components in a section prior to erection. Installing components during pre-outfitting requires significantly less effort than installing the

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same component on the slipway or quay due to increased access, less crowded working conditions and reduced travelling distance (Schank et al. 2005).

The Section Building Planning is often created with vastly insufficient consideration of 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 can result in crowded working conditions, a failure to pre-outfit as many components as possible, disorganisation and rework. Automatic detailed outfitting planning methods, such as the works of Wei (2012), König et al. (2007) and Rose and Coenen (2015), also require a Section Building Planning which adequately considers the required time for pre-outfitting.

A high-quality Section Building Planning has two main characteristics. First, this planning 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 minimised since performing the required steelwork is of strategic importance to the shipyard.

Thus far, no research has been published on the automatic generation of a Section Building Planning specifically tailored to the needs of European shipyards building complex ships by including both the effects of outfitting and outsourcing. The goal of this research is to develop a method for automatically generating such a planning. 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 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.

2. 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 minimise the makespan of the spatial scheduling of the section assembly process and show their algorithm outperforms grid algorithms and manual methods. Zheng, Jiang, and Chen (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, Huat, and Wee (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, Logendran, and Choi (2011) develop a two-dimensional packing model for the spatial 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, Sheen, and Kim (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 create detailed assembly schedules for single sections. Cho, Lee, and Chung (1996) develops 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 the assembly process, cutting and welding operations. Cho, Sun, and Oh (1999) develops 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 researches are not directly applicable to the global planning of the section assembly process since the sections are considered individually.

Kim, Kang, and Park (2002) use a constraint-based approach to create a Section Building Planning which considers both the number of sections that must be outsourced and distribution of the required workload. An algorithm based on the Constraints Satisfaction Problem technique is proposed to solve their proposed 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 researches focused on the section assembly process can be addressed by literature from the operations research community, which has excelled at modelling and solving complex planning problems. For example, Pratap, Manoj Kumar et al. (2015) create a mixed integer programming model for 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

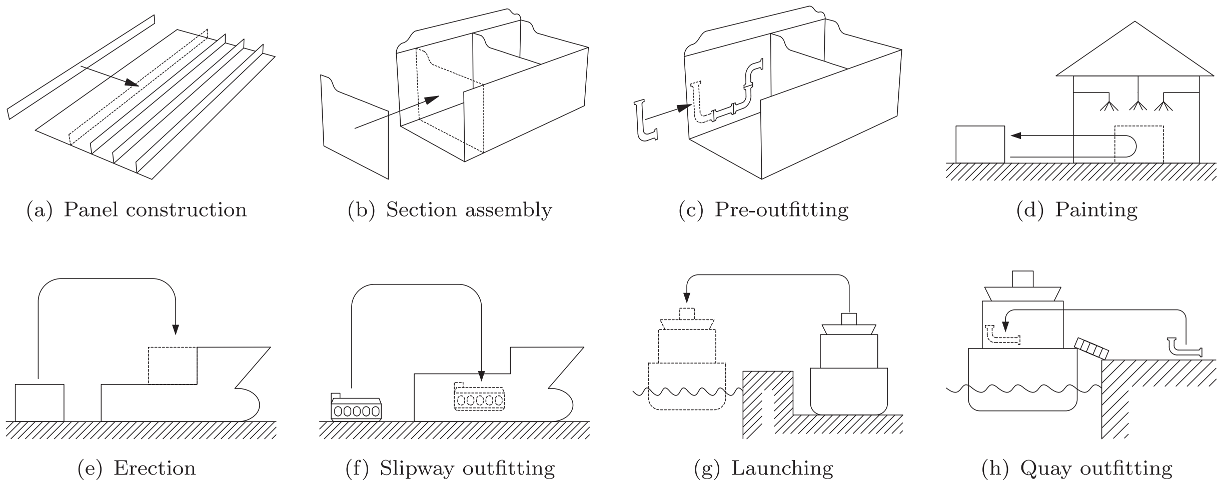

Figure 1. Main shipbuilding activities.

wafers, seeking to optimise 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 optimisation problems. None of the researches of the section assembly process found by the authors constructed Pareto fronts of non-dominated solutions. For example, Berrichi et al. (2010) examine the joint production and maintenance scheduling problem by finding the best assignment for jobs on machines to minimise 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, Nayak et al. (2015) develop a modified version of the NSGA-II to schedule ships berthing in bulk material handing ports, seeking to minimise ship waiting times and deviation from customer priority.

3. Problem description

Figure 1 illustrates the main activities which are performed during the shipbuilding process. Initially, plates and profiles are welded together to form panels. These panels are welded together to form sections during the section assembly process. The installation of pipes, ducting, cable trays and equipment in sections is referred to as pre-outfitting. Once the sections are pre-outfit, they are painted and then erected on the slipway to form the ship's hull. The installation of components on the slipway is called slipway outfitting. Once the hull of the ship is fully erected, the ship is launched and moored at the quay. Outfitting which occurs after launching is referred to as quay outfitting. This paper focuses on the planning of the section building process. This process includes section assembly and pre-outfitting, shown in Figure 1(b) and (c).

For this research, the assumption is made that a shipyard seeks to maximise its capacity in terms of the number of ships delivered. As a result, the Section Erection Planning of the ship is leading and will be used as input for creating the Section Building Planning. The Section Erection Planning indicates the time each section is placed on the slipway. Figure 2 shows an example Section Building Planning for five sections. This figure shows that the sections undergo the erection process in a sequential, non-overlapping manner. The Section Building Planning 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 modelled individually in this paper since that would expand the scope beyond the section assembly process. For example, the resources which are 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

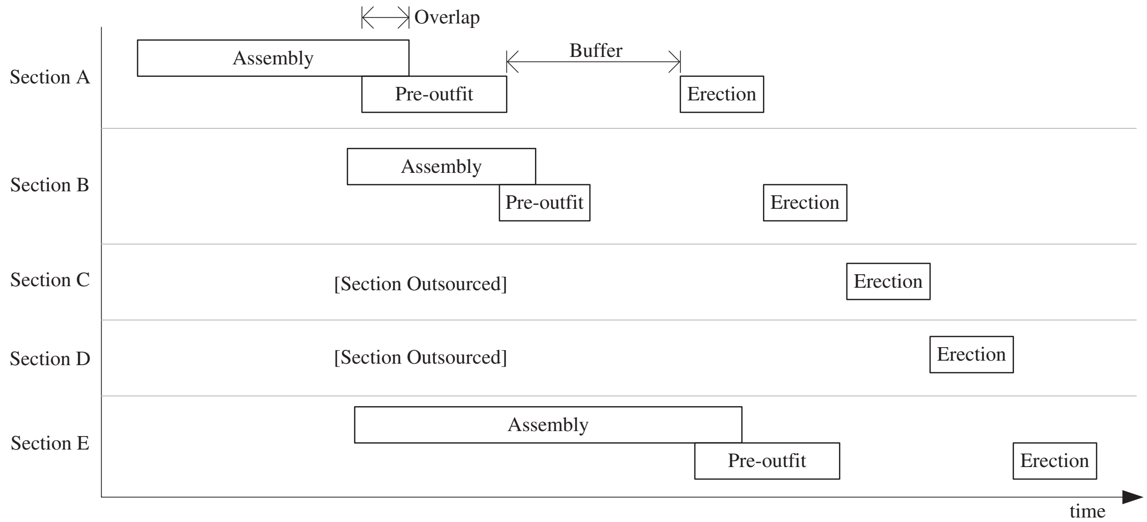

Figure 2. Example section building planning.

sections which are outsourced (C and D). Instead, the assumption is made that the company building the section will have adequate safeguards built into their own planning to deliver the section on time.

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 which can be implemented in a shipyard. First, the pre-outfitting and assembly task have minimum durations. The minimum duration of the assembly process of a section is dictated by the total required man-hours which are required to assemble the section and the number of workers which can safely work simultaneously on that section. The minimum length of the pre-outfitting task is set in such a way that ensures 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. As mentioned in the literature review, European shipyard planners do not typically address this constraint by solving a dynamic two-dimensional 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 3 shows an example of the space constraint for the section building process. Section beds do not necessarily need to be physical locations in the section building hall. They also can be 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 can be directly compared.

The quality of a Section Building Planning depends on two main factors. First, the planning should prevent fluctuations in the required resource levels for all section assembly and outfitting disciplines. Similar to the space constraint, the ideal resource demand curve for a given discipline takes the shape of a trapezoid. This ensures a smooth transition between different

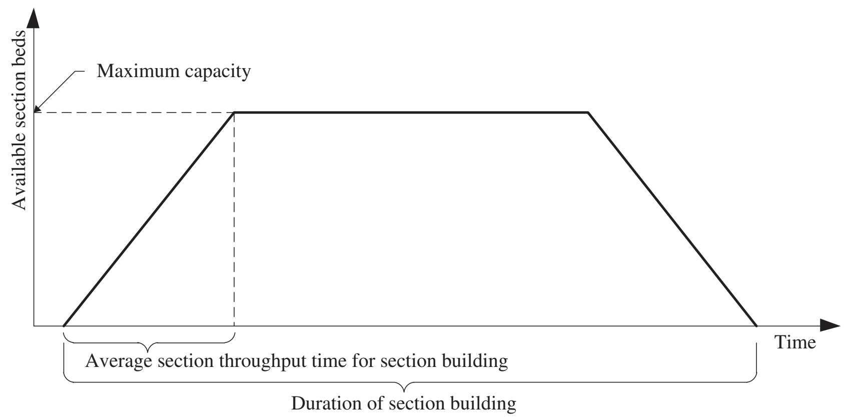

Figure 3. Example space constraint.

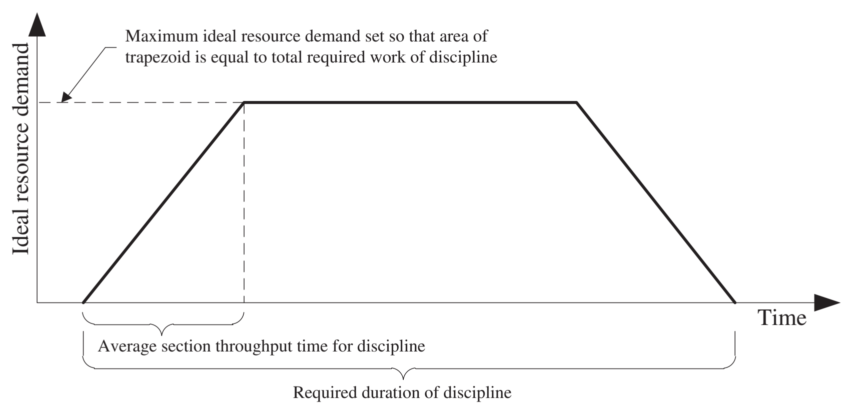

Figure 4. Example ideal resource demand curve.

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 4 shows 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 can be compared with the ideal resource demand curve to assess the quality of the Section Building Planning in terms of resource levelling. 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 levelling objective (Damci and Polat 2014). The total quality of a given Section Building Planning in terms of resource levelling is calculated by summing the individual resource levelling 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. A study was performed by the authors on a series of sections built for a recently delivered pipelaying ship from a Dutch shipyard to determine the accuracy of these manual experience-based predictions. It was concluded 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 Planning can be assessed is the percentage of required work which is performed at the shipyard. An ideal planning 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 processes if performed at the shipyard itself.

Although these two objectives do not absolutely conflict with each other, a trade-off does exist between them. The goal of this research is not to generate the best Section Building Planning when considering both resource levelling 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 Planning for a given ship.

4. 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:

Sets

S = set of a ship's sections
D = set of assembly and outfitting disciplines
T = set of time steps

Indices

$s = \{1, 2, \ldots, S\}$ sections
$d = \{1, 2, \ldots, D\}$ assembly and outfitting disciplines
$t = \{1, 2, \ldots, T\}$ time

Input data

$m_{d,s}$ = required man-hours of discipline d for section s
$i_{d,t}$ = ideal global resource requirement for discipline d at time t

$$c_d = \begin{cases} 1, \text{ if discipline } d \text{ is performed during assembly} \\ 0, \text{ if discipline } d \text{ is performed during pre-outfitting} \end{cases}$$

e_s = erection time of section s
Q = duration of overlap of assembly and pre-outfitting
$\min_{a_s}$ = minimum duration of assembly for section s
$\max_{a_s}$ = maximum duration of assembly for section s
$\min_{p_s}$ minimum duration of pre-outfitting for section s
$\max_{p_s}$ maximum duration of pre-outfitting for section s
$\min_{b_s}$ minimum duration of buffer for section s
$\max_{b_s}$ maximum duration of buffer for section s
h_t = number of section beds available at time t

$$n_s = \begin{cases} 0.5, \text{ if section } s \text{ requires only half a section bed} \\ 1, \text{ otherwise} \end{cases}$$

Decision variables

a_s = duration of assembly for section s
p_s = duration of pre-outfitting for section s
b_s = duration of buffer section s

$$o_s = \begin{cases} 1, \text{ if section } s \text{ is outsourced} \\ 0, \text{ if section } s \text{ is built on-site} \end{cases}$$

$$x_{s,t} = \begin{cases} 1, \text{ if section } s \text{ is in assembly at time } t \\ 0, \text{ otherwise} \end{cases}$$

$$y_{s,t} = \begin{cases} 1, \text{ if section } s \text{ is in pre-outfitting at time } t \\ 0, \text{ otherwise} \end{cases}$$

Objectives

O_{out} = outsourcing objective
O_{res} = resource objective

Objective functions

$$O_{\text{out}} = \frac{\sum_{d\in D} \sum_{s\in S} m_{d,s} o_s}{\sum_{d\in D} \sum_{s\in S} m_{d,s}} \tag{1}$$

$$O_{\text{res}} = \sum_{d\in D}\sum_{t\in T} c_d\left(i_{d,t} - \sum_{s\in S}\frac{m_{d,s}x_{s,t}}{a_s}\right)^2 + \sum_{d\in D}\sum_{t\in T}(1-c_d)\left(i_{d,t} - \sum_{s\in S}\frac{m_{d,s}y_{s,t}}{p_s}\right)^2 \tag{2}$$

Constraints

$$\min_{a_s} \le a_s \le \max_{a_s} \quad \forall s \in S \tag{3}$$
$$\min_{p_s} \le p_s \le \max_{p_s} \quad \forall s \in S \tag{4}$$
$$\min_{b_s} \le b_s \le \max_{b_s} \quad \forall s \in S \tag{5}$$
$$x_{s,t} = 0 \quad \forall s \in S, t < (e_s - b_s - p_s + Q - a_s), o_s = 0 \tag{6}$$
$$x_{s,t} = 1 \quad \forall s \in S, (e_s - b_s - p_s + Q - a_s) \le t < (e_s - b_s - p_s + Q), o_s = 0 \tag{7}$$
$$x_{s,t} = 0 \quad \forall s \in S, t \ge (e_s - b_s - p_s + Q), o_s = 0 \tag{8}$$
$$y_{s,t} = 0 \quad \forall s \in S, t < (e_s - b_s - p_s), o_s = 0 \tag{9}$$
$$y_{s,t} = 1 \quad \forall s \in S, (e_s - b_s - p_s) \le t < (e_s - b_s), o_s = 0 \tag{10}$$
$$y_{s,t} = 0 \quad \forall s \in S, t \ge (e_s - b_s - p_s), o_s = 0 \tag{11}$$
$$x_{s,t} = 0 \quad \forall s \in S, \forall t \in T, o_s = 1 \tag{12}$$
$$y_{s,t} = 0 \quad \forall s \in S, \forall t \in T, o_s = 1 \tag{13}$$
$$\sum_{s\in S} \max(x_{s,t}, y_{s,t}) n_s \le h_t \quad \forall t \in T \tag{14}$$

Equations (1) and (2) calculate the outsourcing and resource objectives, both of which should be minimised. Equations (3), (4) and (5) ensure that the duration of each section's assembly, pre-outfitting and buffer is within the allowed limits. Equations (6) through (11) determine during which time steps each section that is built on-site undergoes assembly and pre-outfitting. Equations (12) and (13) ensure that all sections which are outsourced are never in assembly or pre-outfitting. Equation (14) limits the number of sections which can be built on-site at each point in time.

5. Methodology

Genetic algorithms are a meta-heuristic optimisation technique loosely based on the biological process of evolution. This optimisation approach was selected because literature has shown that genetic algorithms are capable of effectively solving complex scheduling problems. Specifically, the NSGA-II was implemented. A complete description of this algorithm can be found in Deb et al. (2002). The NSGA-II was selected to automatically generate section building schedules for several key reasons. First, the NSGA-II is designed for multi-objective optimisation 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 optimisation 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, Chua, and Yeoh 2011), develop a decision support system for bulk material handling ports (Pratap, Nayak et al. 2015), schedule joint production and maintenance (Berrichi et al. 2010), solve the generation expansion planning problem (Murugan, Kannan, and Baskar 2009) and for hydro-thermal power scheduling (Deb and Karthik 2007).

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 Planning and then assesses that planning based on its resource demands and outsourcing requirements. Because genetic algorithms can perform poorly

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

Figure 5. Chromosome representation.

Step 1. Set $o_s = 0\ \forall s \in S$

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

- (a) $a_s = min_{a_s} + (max_{a_s} - min_{a_s}) * X_{a_s}$
- (b) $p_s = min_{p_s} + (max_{p_s} - min_{p_s}) * X_{p_s}$
- (c) $b_s = min_{b_s} + (max_{b_s} - min_{b_s}) * X_{b_s}$

Step 3. Calculate $x_{s,t}$ and $y_{s,t}$ $\forall s \in S, \forall t \in T$

Step 4. If space constraint (Equation 14) is satisfied, go to Step 6

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

- (a) $o_s = 0$
- (b) $x_{s,t} = 1$ or $y_{s,t} = 1$ for some t where $\sum_{s \in S} max(x_{s,t}, y_{s,t}) n_s > h_t$

Step 6. Calculate O_{out} and O_{res}

Figure 6. Fitness function.

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 Planning. Figure 5 shows the chromosome representation used. Every section is described by four genes, where X_{a_s}, X_{p_s} and X_{b_s} are factors used to calculate the duration of assembly process, pre-outfitting process and buffer, respectively, of section $s \in S$. Each section also has an outsourcing priority X_{o_s}. Each gene can take any real value between zero and one, so that $0 \leq X \leq 1$. Figure 6 shows the fitness function used to transform each chromosome into a feasible Section Building Planning and assess the quality of the planning.

The NSGA-II parameters used by Deb et al. (2002) were implemented, with the exception of mutation rate. Deb et al. used a population size of 100, mutation rate of 1/chromosome length, crossover probability of 0.9, distribution index for crossover of 20, a distribution index for mutation of 20 and a constant stopping condition of 250 generations. Because the performance of the genetic algorithm was satisfactory when using these parameters, no further effort was performed to optimise these parameters. However, additional improvement in both solution quality and computational time may be attainable by tuning all of the NSGA-II parameters. This can be done experimentally or through the use of a tuning procedure. An overview of the different parameter tuning methods found in literature for evolutionary algorithms can be found in Eiben and Smit (2011).

6. Test case

Four test cases were performed of ships recently delivered from Royal IHC, a Dutch shipbuilding group. This was done to demonstrate the feasibility of both the mathematical model and solution approach developed in this paper. The first two test cases (A and B) were pipelaying ships, and the second two test cases (C and D) were trailing suction hopper dredgers. Table 1 shows the characteristics of these ships.

Input from experienced shipyard planners as well as an analysis of past section building schedules was used to set the task duration limits. Factors such as the workforce size and the number of shifts employees worked during the construction of the ship were also taken into account. The maximum task durations were set to be arbitrarily large, four times the minimum durations, but capped at a practical limit due to the consideration of storing the completed sections at the shipyard. The baseline Section Erection Planning created by the erection planners was used to determine the erection time of each section.

Royal IHC planners estimate the total required man-hours for the assembly task of each section, and these predictions were used for the test cases. The actual hours required to assemble the sections were not used since this information is not available when making the Section Building Planning. Table 2 shows 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. Eight per cent 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

Table 1. Test case characteristics.

Test case	A	B	C	D
Number of sections ($\|S\|$)	112	111	60	133
Definition of small sections ($n_s = 0.5$)	<100 m^2	<100 m^2	<100 m^2	<100 m^2
Minimum assembly duration ($\min_{a_s}$)	20 days	20 days	15 days	20 days
Maximum assembly duration ($\max_{a_s}$)	60 days	60 days	45 days	60 days
Minimum pre-outfitting duration ($\min_{p_s}$)	5 days	5 days	5 days	5 days
Maximum pre-outfitting duration ($\max_{p_s}$)	15 days	15 days	15 days	15 days
Minimum buffer duration ($\min_{b_s}$)	15 days	15 days	10 days	15 days
Maximum buffer duration ($\max_{b_s}$)	45 days	45 days	30 days	45 days
Overlap duration (Q)	5 days	5 days	5 days	5 days

Table 2. Outfitting disciplines and tasks considered in test case.

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

used to determine the required number of outfitting tasks per section required for the piping and electrical disciplines. The methodology developed by Wei (2012) was used to determine the number of man-hours required for the installation of pipe spools. A tool developed at Royal IHC for predicting the workload per section for heating, ventilation and air conditioning (HVAC) and secondary steel tasks was used to estimate the man-hours required for these disciplines. This tool also suggests a method for calculating the man-hours required to install cable trays, which were used to determine the man-hours per section required for the electrical discipline.

7. Results

Ten trials where run for each of the test cases, and Pareto fronts were created using the non-dominated solutions found from these trials, shown in Figure 7. The position of the Section Building Planning created by the shipyard planners is also shown in this figure. Shipyard planners use their own experience and manual calculations to generate these production schedules. Figure 7 suggests that additional gains can be realised in terms of both of the examined objectives for each of the test cases compared to the Section Building Planning actually used when constructing these ships. The optimisation was performed using MATLAB and required roughly 2 min to run on a PC with 16-GB RAM and an 8 × 3.50-GHz processor.

The ship used in test case C is significantly smaller than the other three ships, composed of roughly half as many sections. This can be seen in Figure 7(c), where the NSGA-II was able to find a solution where no sections were outsourced ($O_{out} = 0$). The solution created by the shipyard planners only outsourced a single section. The remaining three test cases, all of roughly the same size, required that roughly half of the man-hours were outsourced.

Each Section Building Planning created by the shipyard planners marginally violates the process constraints at times, specifically the space constraints and minimum buffer duration constraints. When asked about these violations, the planners indicated that these constraints were at times flexible, but local factors (such as complexity of required work and availability of overtime) need to be taken into account when violating these constraints. In the future, the methodology presented in this paper could be expanded to take into account the flexible nature of these constraints. However, the planners also expressed that they would prefer to create a Section Building Planning which does not violate any of the constraints, but are generally not able to generate such a planning in the time allotted to them for making the planning. Figure 7 shows that it is possible to create high-quality production schedules using the methodology developed in this paper while applying these constraints stringently.

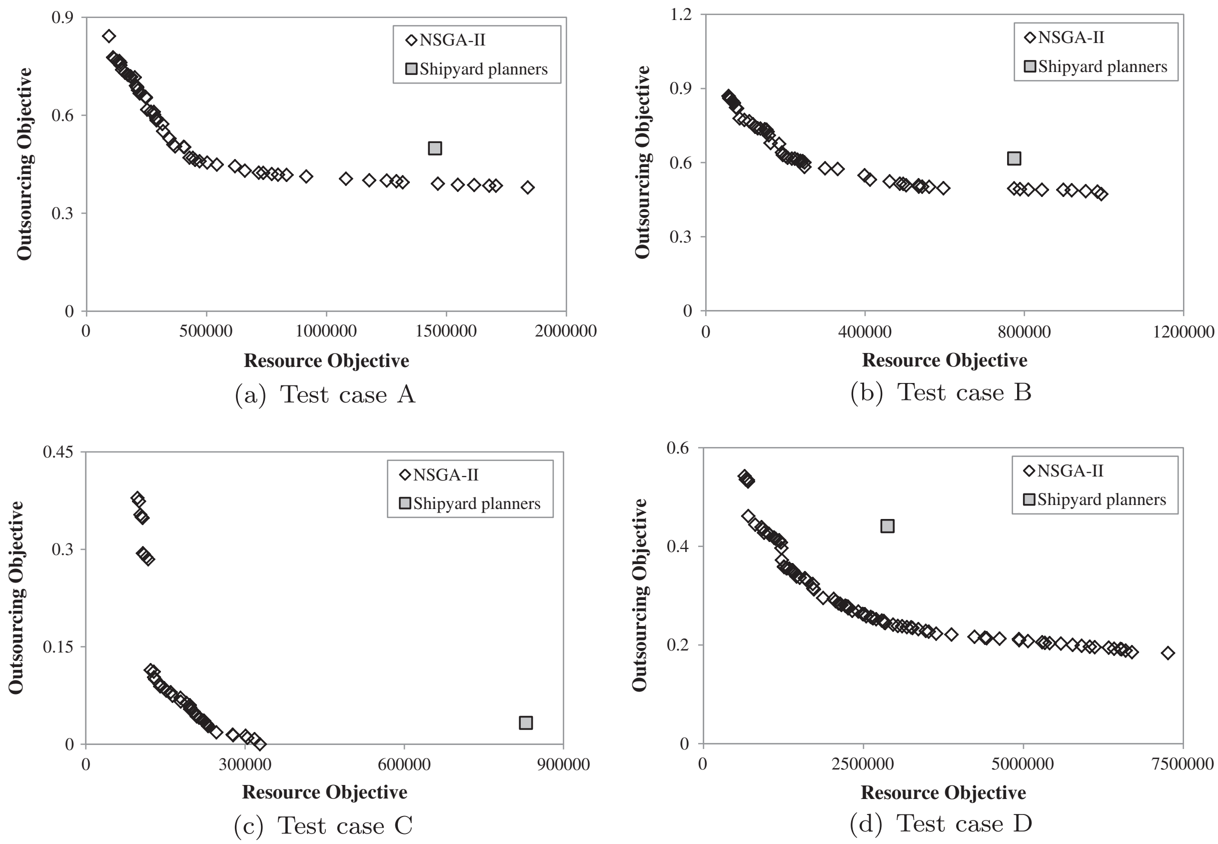

Figure 7. Pareto fronts for test cases.

8. Implementation

The methodology developed in this paper is not designed to replace existing section building planners, but instead enhance their decision-making abilities. This type of approach can be easily integrated in the current work flow of these planners. For example, the section building planners of the shipyard building the test case ship already use a crude Microsoft Excel-based tool to generate an initial Section Building Planning. This tool takes the section characteristics and Section Erection Planning as input and builds a Section Building Planning using rules of thumb to estimate task durations. The planners then manually select which sections to outsource and adjust the planning 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 could replace such a tool. The judgement of the planners would be required to select one of the several promising schedules to be the starting point of the Section Building Planning. The selection of the promising schedules to further investigate could be done using a combination of crowding distance and the strategic goals set by the shipyard. For example, a shipyard might desire to build a minimum number of man-hours on-site to maintain their own section building capacity. Such a limit would restrict the allowable solutions with outsourcing objectives above this limit. Furthermore, planners would still be able to adjust the schedule to fit the specific constraints of the project. For example, some section types (such as the extremely curved bulbous bow sections) can be of strategic interest to a shipyard, and therefore the shipyard may want to build these sections on-site. Delays in the previous project or additional work from side project might also require that adjustments be made to the Section Building Planning.

However, only generating an initial optimised Section Building Planning does not guarantee a smooth execution of the process throughout its entire duration. To accomplish this, an integrated approach should be implemented. Phanden, Jain, and Verma (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 section building 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 would be possible to re-optimise the Section Building Planning each week to account for these disturbances. Ultimately, the aim is to create a fully integrated system for managing the section building process, such as the system designed by Mourtzis (2005) for ship repair operations.

9. Conclusion

This paper defines the section building process as a bi-objective scheduling problem which seeks to minimise the amount of outsourced work and the variations in the resource requirements. A solution technique, based on the NSGA-II, was developed and tested using four test cases. For each test case, it was possible to quickly generate a diverse set of high-quality section building schedules. The quality of these schedules exceeded that of those manually created by the shipyard planners with respect to both objectives. Implementing an automatic section building planning method such as the one presented in this paper can not only increase the overall quality of the Section Building Planning used during a ship's production, but can also reduce the time required to create this planning.

For this research, the Section Erection Planning was used as an input to generate a Section Building Planning. Currently, the Section Erection Planning is being manually generated by experienced shipyard planners (much like what is currently done for the Section Building Planning). The mathematical model and solution technique presented here will be expanded to include the planning of the section erection process. To do this, additional erection-related constraints and disciplines must be included. Because of the interdependencies between the section building and section erection processes, optimising these processes simultaneously can lead to even greater benefits than examining only the section building process.

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