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OPTIMIZED BALANCING OF PRODUCTION WITH DEMAND IN SHIPYARDS: METHODOLOGY APPLIED TO A REAL CASE

BALANCEAMENTO OTIMIZADO DA PRODUÇÃO COM A DEMANDA EM ESTALEIROS NÁUTICOS: METODOLOGIA APLICADA EM CASO REAL

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ABSTRACT

Purpose: The aim of this study is to propose a methodology for optimizing the aggregate planning problem in shipyards and to illustrate its application in a real case. The methodology should be generic and flexible so that it can serve as a reference for application in any small-scale shipyard. **Theoretical framework**: Aggregate planning is the process of balancing production with demand, typically projected over time horizons of six to twelve months. This balancing act involves adjusting productive resources, aiming to simultaneously meet demand while minimizing costs. **Methodology/Approach**: The study introduces a generic methodology applicable to aggregate planning in small nautical shipyards. It comprises the following steps: measuring capacity, forecasting demand, selecting the appropriate capacity policy for production management, and finally, proposing an optimal aggregate planning alternative. **Findings**: The methodology proved to be viable for application in a real-life case, demonstrating its suitability for the specific industry. The time required to apply this methodology in a small shipyard (with fewer than 20 employees) can be estimated at one to two weeks. This methodology could also be implemented as consultancy for industries in the sector due to its numerous benefits. **Research, practical & social implications**: The study presents a new technology for planning and controlling production in the Brazilian nautical market, fostering its growth and international competitiveness. As a consequence, the development of the national industry leads to the creation of new jobs. **Originality/Value**: The value of the study lies in its direct contribution to professional practice, providing a valuable reference for production planning in similar industries. The paper presents an original aggregate planning methodology, demonstrated through a case study in nautical shipyards. The results obtained demonstrate the effectiveness of the approach in minimizing production costs.

Keywords: Nautical industry; Nautical shipyard; Aggregate planning; Linear programming; Capacity planning

RESUMO

Objetivo: O objetivo deste estudo é propor uma metodologia para otimização do problema do planejamento agregado em estaleiros náuticos e ilustrar sua aplicação em um caso real. A metodologia deve ser genérica e flexível, de forma que possa servir como referência para aplicação em qualquer estaleiro náutico de pequeno porte. **Referencial Teórico**: O planejamento agregado é o processo de balanceamento da produção com a demanda, projetada para horizontes de tempo em geral de seis a doze meses. Esse balanceamento pode ser feito atuando-se sobre os recursos produtivos. Nesse processo, o que se procura é combinar esses recursos de maneira a, simultaneamente, atender à demanda e obter custo mínimo. **Metodologia/Abordagem**: O estudo apresenta uma metodologia genérica que pode ser aplicada ao planejamento agregado na maioria das empresas. Ela consiste nas etapas: medir a capacidade, prever a demanda, escolher a política de capacidade adequada para a gestão da produção e, por fim, propor a alternativa ótima de planejamento agregado. **Resultados**: A metodologia utilizada mostrou-se viável em caso real, demonstrando que pode ser seguida a fio para o tipo de indústria em questão. O tempo necessário para aplicar essa metodologia em um estaleiro de pequeno porte (com menos de 20 funcionários) pode ser estimado em 1 a 2 semanas. Essa metodologia pode, inclusive, ser implantada como forma de consultoria para as indústrias do segmento, devido aos seus vários benefícios. **Contribuições, implicações práticas e sociais**: O estudo apresenta uma nova tecnologia para planejamento e controle da produção ao mercado náutico brasileiro, fomentando seu crescimento e competitividade internacional. Como consequência, o desenvolvimento da indústria nacional acarreta a geração de novos empregos. **Originalidade/Valor**: O valor do estudo consiste em sua contribuição direta para a prática profissional, fornecendo uma referência valiosa para o planejamento de produção em indústrias semelhantes. O trabalho apresenta uma metodologia original de planejamento agregado, demonstrada em um estudo de caso em estaleiros náuticos. Os resultados obtidos mostram a eficácia da abordagem na minimização dos custos de produção.

Palavras-chave: Indústria náutica, estaleiro náutico, planejamento agregado, programação linear, planejamento da capacidade.

Introduction

This study falls within the field of Production Planning and Control, more specifically in the context of Aggregate Planning for nautical construction, characterized by low volume and a low degree of customization. Aggregate planning is the process of balancing production with projected demand over time horizons generally ranging from six to twelve months, according to Moreira (2012). The focus of the study is on the market segment of sport and leisure boats, i.e., any vessel capable of moving on water, whether self-propelled or not, designed for transporting people or goods in the context of recreational and sport-related activities without commercial purposes, as defined by DPC (2023).

Regarding the context in which this research is situated, it is observed that Brazil has immense and internationally recognized potential for the construction of sport and recreational vessels, as evidenced by the recent interest of major multinational companies in the nautical sector seeking to establish connections with the country. The national industry faces unprecedented challenges and opportunities, and to address them, it must demonstrate its ability to employ the tools demanded by the market: consistent information, strategic thinking, and human talent.

The expansion and increasing formalization of the sector's activities have led to the emergence of numerous new companies—many of them micro or small businesses—generating employment and income. This has created favorable conditions for tax burden rationalization, including reductions in the IPI (Tax on Industrialized Products) and ICMS (Goods and Services Tax) rates in key states such as São Paulo, Rio de Janeiro, Santa Catarina, and Bahia. According to Acobar (2012), despite this promising scenario and Brazil's unparalleled potential in the field, the national nautical sector still faces significant challenges and bottlenecks across its entire value chain, both inbound (production and sale of vessels) and outbound (use of vessels and related services).

The Southeast and South regions of Brazil concentrate over 85% of the shipyards, with São Paulo accounting for 35% of the total, followed by Santa Catarina (21%) and Rio de Janeiro (14%). Currently, the market includes approximately 120 formal shipyards in operation, producing vessels of 16 feet or more. Still according to Acobar (2012), the nautical production chain in Brazil has strong potential for job creation throughout its links and, therefore, holds significant potential for social impact. The number of workers employed in shipyards specializing in the construction of sport and recreational vessels in Brazil is estimated at 9,800 people, while manufacturers of accessories, parts, and equipment employ approximately 7,000 workers.

From the perspective of production management in these shipyards, the literature shows the application of aggregate planning models using different mathematical approaches, such as linear programming and heuristics, in sectors like textiles, drill bits, sugar and ethanol, and agricultural seeds. However, there is a notable gap in the application of these methods to the nautical industry, especially in the leisure segment, which presents specific production characteristics such as high seasonality, low production scale, and customization requirements. Moreover, none of the reviewed studies presents a step-by-step structured model specifically for aggregate planning in nautical shipyards. According to Oliveira (2011), the seasonal nature of sport and recreational boat sales demands dynamic management of the production system, quick responses to demand fluctuations, and careful analysis of labor capacity utilization. Therefore, applying an optimization-based approach to support operational decision-making processes is considered fundamental for Brazil’s economic development in the sports and leisure sector.

Matching production with demand over time is a core responsibility of production management. An appropriate balance between supply and demand can minimize costs while keeping customers satisfied, whereas imbalances may result in idle labor, unnecessary inventories, customer loss, and related costs. According to Slack et al. (2010), this balance is essential for operational efficiency.

The proposed methodology is applied to a shipyard specializing in sport and recreational boats, whose main product is the dinghy—a 4.16-meter-long sailboat widely used for racing and sailing instruction. The dinghy is a one-design sailboat, meaning it is built following standardized construction rules and specifications, ensuring consistency in its dimensions, shape, and features over time. It was created in 1978 with the aim of being used for family outings and competitive events, such as regattas. It became popular due to its affordability and ease of handling. Since then, more than 4,080 dinghies have been sold in Brazil. For further information about the dinghy, refer to the Brazilian Dinghy Class Association (2025).

At the shipyard where it is manufactured, the production process can be characterized as a batch production system with intermittent flow, according to Moreira (2012), featuring small batches with repetitive characteristics and low customization. The shipyard is located in the state of Santa Catarina, along the BR-101 corridor, in the most important nautical hub of the region and the third-largest in Brazil, behind only the coastal areas of Rio de Janeiro and São Paulo, as stated by Acobar (2012).

Therefore, this study contributes by proposing a novel and structured methodology for aggregate planning, specifically tailored to the Brazilian nautical industry, which currently lacks models suited to its particular production characteristics. This proposal aims to fill a methodological gap in the literature and serve as a practical reference for managers in the sector.

This paper is organized as follows: first, this initial section (Introduction) briefly introduces and contextualizes the objectives of the study. Next, Section 2 (Literature Review) presents a literature review outlining the state of the art of aggregate planning in the nautical industry using optimization tools, along with its justification and relevance for Brazilian production management. Section 3 (Methodology) presents the proposed methodology, developed in response to the lack of a systematic step-by-step process for aggregate planning in nautical shipyards. Section 4 (Results and Discussion) applies the proposed methodology to the aggregate planning of a nautical shipyard, detailing the required calculations and presenting the obtained results. Finally, this section includes a discussion on the methodology and its outcomes. Section 5 (Conclusion) presents the conclusions of the study, including suggestions for future research.

Literature Review

The body of literature on Production Planning and Control applied to the nautical and/or naval industries remains limited in both volume and scope. A literature review was conducted using databases such as Capes Periodicals and Google Scholar. The search identified ten scientific articles, one master's thesis, and three undergraduate final papers (commonly known as "TCCs" in Brazil). This section presents the main studies identified, with emphasis on the methodological approaches employed and the industrial contexts in which they were applied.

Seven of the reviewed studies focus on aggregate planning applied to segments of the manufacturing industry. The first, by Pasa et al. (2017), proposes profit maximization for a car siren company using aggregate planning. In a more recent article, Gassen et al. (2019) developed a linear programming model to optimize the aggregate production planning of drill bits. In the master's thesis by Jesus (2014), a mathematical model was created to represent the production system of a company that manufactures equipment for mineral analysis. In the article by Paiva and Morabito (2007), an optimization model was implemented for the aggregate production planning of sugar and ethanol mills; Junqueira and Morabito (2006) implemented a similar model for the aggregate planning of production and logistics of corn seeds; in the study by Munhoz and Morabito (2010), a similar approach was applied to the frozen orange juice concentrate industry; finally, Oliveira (2011a) conducted a study focused on the textile industry. These studies employed various optimization techniques—mostly linear programming—with the aim of reducing costs, aligning production with demand, and improving resource allocation. The advantages of these models include the ability to simulate scenarios and make data-driven decisions, while the challenges include modeling complexity and the need for reliable data.

The undergraduate thesis by Júnior (2018) and the article by Barbosa et al. (2016) address the development of a project management methodology using PERT, applied to an As-Built project (with documented technical representations) of a fiberglass boat. These studies share elements with the production planning stage, such as system characterization and time estimation, but do not cover capacity management models or aggregate planning approaches.

The study by Cordeiro et al. (2015) stands out for its detailed presentation of mathematical equations used to model a constant production strategy aligned with demand. Using Excel in conjunction with Visual Basic for Applications, the study illustrates equations related to various aspects of production, such as regular production, hiring, layoffs, and cost calculations, providing a clear and quantitative approach that may serve as a reference for future research.

The article by Oliveira (2014) evaluates project management maturity in a shipyard in northeastern Brazil, using Prado's Project Management Maturity Model (2010). Although it uses a different methodology from that of the present study, it aims to improve business outcomes by identifying weaknesses, strengths, and bottlenecks in pursuit of continuous improvement. This methodology could complement aggregate planning research in future studies, although it depends on the availability and reliability of managerial responses to generate accurate results.

Filho et al. (1995) addressed the solution of an optimal production planning problem with a focus on inventory behavior, using non-negativity constraints on production and inventory levels, the latter being constrained probabilistically. However, this methodology does not contribute to the current research, as it focuses primarily on inventory, whereas the present study emphasizes production variables within aggregate planning.

Aurélio Schmidt et al. (2017) propose a nautical industry product aimed at operational efficiency and eco-design to reduce waste. The study focuses on the product development stage and environmental concerns, without covering production management.

In the master's thesis by Oliveira (2011), production planning optimization in a nautical shipyard is carried out using a computational system based on Mixed-Integer Linear Programming. The objective is to minimize idle time at the production bottleneck. The study is divided into five stages, including the identification of production models and the programming of software to find the best solution.

In summary, the reviewed literature presents a variety of production planning models applied to different industrial sectors, with a predominance of approaches based on mathematical optimization. Studies specifically targeting the nautical industry are scarcer, and when they exist, they often address aspects complementary to aggregate planning, such as project management, product development, or organizational maturity.

Justification and contribution

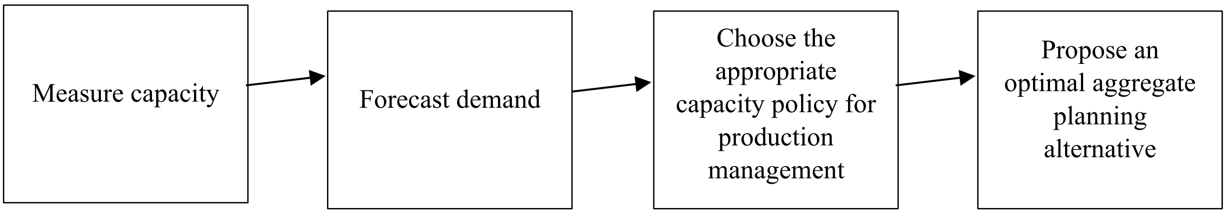
The distinguishing feature of this study lies in the development of a new approach to aggregate planning in the nautical industry. As shown in the literature review, to the best of the authors' knowledge, there is no existing methodology that provides a structured step-by-step process for performing aggregate planning in nautical or naval shipyards. Therefore, this study is pioneering in this regard, as it proposes an original, generic, and flexible methodology that can be applied by any shipyard, anywhere in the world. Furthermore, the proposed methodology is illustrated through its application in a real-world case (a nautical shipyard located in the state of Santa Catarina, Brazil), which aims to make the theoretical approach more accessible to the reader while also enabling engineers, managers, and other stakeholders to use this study as a reference for further applications in other shipyards.

Methodology

The proposed methodology shares similarities with the "Aggregate Planning Steps" methodology presented by Moreira (2012). However, specific adaptations were made to provide tailored guidance for nautical shipyards. The resulting methodology is composed of four steps (Figure 1), namely: (i) measure capacity; (ii) forecast demand; (iii) choose the appropriate capacity policy for production management; and (iv) propose an optimal aggregate planning alternative.

Figure 1.

Steps of the proposed methodology.



For the purposes of this study and to facilitate understanding of the methodology and its results, the following definitions, adapted from Moreira (2012), are considered:

- *Aggregate planning* is the tactical process of balancing production and demand in the medium term, aiming to meet demand fluctuations at the lowest possible cost through capacity, inventory, or demand adjustments;
- *Planned production* refers to the production volume defined for each period within the aggregate plan, adjusted to align projected demand and available capacity by means of policies such as overtime, layoffs, inventory use, or subcontracting;
- *Capacity* is the maximum quantity of goods or services that a production unit can generate in a specific period, primarily determined by the availability of physical space and machinery. It is considered fixed in the short and medium term, that is, throughout the aggregate planning horizon (typically 6 to 12 months). Capacity may change through exceptional measures that require substantial investments (e.g., expansion of physical space, investment in new machines, automation), which are beyond the scope of aggregate planning. These changes are addressed in capacity planning (10 to 20-year horizon), which lies outside the scope of this study;
- *Forecast demand* refers to the projected demand over a medium-term horizon (usually 6 to 12 months). It is the main input of aggregate planning and is based on statistical and historical methods.

Measuring capacity

In this initial step, the method for measuring capacity must be defined. Capacity can be measured either by production output (e.g., units of products such as boats) or by the inputs used in the production process. Measuring output is most appropriate when only one product is involved. In cases where multiple products exist, it may be more suitable to express capacity in terms of the inputs used to produce goods or services.

In the latter case, it is important to note that mixing different input measures—such as tons, kilograms of resin, units of boats, etc.—is impractical during capacity analysis. Measuring capacity involves defining the maximum quantity of products or services that a production unit can produce within a given time period—for instance, each period may correspond to a month. It is essential not to exceed the basic reference of the capacity definition: regular production cannot exceed 100% of available capacity, as established by Moreira (2012).

It is worth highlighting that in the specific case of this study, the shipyard's production process is not classified as a project-based system, since the boats produced are only minimally customized. The dinghy sailboat is a standardized product with well-defined and consolidated dimensions, shape, and characteristics, with only a few optional items added or customized at the end of the production chain. Thus, the production process presents the characteristics of a batch production system, as described by Moreira (2012), featuring small batch sizes (low volume) but with repetitive patterns.

This type of process allows for the application of aggregate planning, using aggregate production measures based on standardized resources, such as operator labor hours or mold availability. This approach is compatible with the management of intermittent, repetitive production and is not intended as a tool for project-based manufacturing environments.

Based on this production system characterization, it becomes possible to apply a capacity calculation model focused on identifying the bottleneck resource. To calculate the shipyard's capacity, the first step is to determine which resource limits the production capacity. This constraint may be labor, equipment, raw materials, physical space, or technology. Once the limiting resource is identified, it is necessary to determine how many units of product this resource can produce per hour—i.e., its production rate, denoted as T', as shown in Equation 1:

$$T' = \frac{Total\ produced}{Elapsed\ Time} \quad (1)$$

To calculate production capacity, the production rate of the resource is multiplied by the number of hours available in the planning period, as shown in Equation 2. When labor is the limiting resource, capacity can be calculated using Equation 3, where F represents the number of workers and CH is the number of hours worked per employee during the period (hours/month):

$$Capacity = Available\ Time\ x\ Production\ Rate \quad (2)$$

$$Capacity = F \times CH \times T' \quad (3)$$

Forecasting demand for the following year

In this step, a method must be selected to forecast demand for the desired period. According to Moreira (2012), the main factors for choosing a forecasting method are data availability, time and resources, and the forecasting horizon. Moreira (2012) presents several demand forecasting methods in the literature. These can be categorized into three groups: qualitative methods, causal methods, and time series methods.

- **Qualitative methods for demand forecasting**: executive opinion, sales force opinion, consumer surveys, and the Delphi method;
- **Causal methods for demand forecasting**: simple linear regression, correlation and determination coefficients, nonlinear simple regressions, and multiple linear regression;
- **Time series methods for demand forecasting**: time series decomposition model and moving average methods.

Time series decomposition model

The use of the time series decomposition model allows, optionally, for the consideration of seasonality and random factors in demand forecasting, according to Moreira (2012). This model was effectively used in this study, as it is appropriate for the context of the shipyard, which shows monthly demand fluctuations related to seasonality. The model can be represented by the equation shown in Table 1.

Table 1

Forecast Demand Equation.

Equation	Variables
$Y = (T).(S)$	Y = Time series value (forecast demand) T = Trend component S = Seasonal component

The application of this model allows for the explicit consideration of both trend and seasonal components, which are essential for accurately forecasting demand over time. Seasonality was incorporated based on historical monthly data and is detailed in Table 12, in the Results section.

Although monthly production quantities are relatively low, the company's production process is standardized and repetitive (a single model for hull, deck, mast, and finishing), which characterizes the system as batch production with intermittent flow and repetitive features, according to Moreira (2012). Therefore, the use of aggregated and quantitative models, such as decomposition, is justified.

This model also requires the definition of a function to represent the demand trend line ($\hat{Y}$). A linear function is suggested, as shown in Equation 4. To do this, time values (*t*) are used to represent the periods (months in this case), and the trend line equation is determined using the least squares method or Excel's suggestion, thus obtaining values for *a* and *b*.

$$\hat{Y} = a + b.t \qquad (4)$$

Once the trend line equation is defined, the next step, according to Moreira (2012), is to calculate the coefficient of determination (Table 2). The coefficient ranges from 0 to +1 and is interpreted as the proportion of shared variance between *y* and *t* — that is, the proportion of *y*'s variation explained by *t*'s variation.

Table 2

Equation of the Coefficient of Determination.

Equation	Variables
$r^2 = \frac{\sum(\hat{Y} - \bar{Y})^2}{\sum(Y - \bar{Y})^2}$	Y = Actual demand values $\hat{Y}$ = Forecast demand values $\bar{Y}$ = Mean of actual demand values

Next, the trend component must be calculated for each future period, where n represents the number of past periods used as a sample. In this case, a monthly forecast for the following year is made, so the calculation goes up to the 12th period, as shown in Figure 2.

Figure 2

Equations of Trend Components for Three Periods.

1st Period (t = n + 1): $\hat{Y}_{n+1} = T_{n+1} = a + b.(n + 1)$

2nd Period (t = n + 2): $\hat{Y}_{n+2} = T_{n+2} = a + b.(n + 2)$

3rd Period (t = n + 3): $\hat{Y}_{n+3} = T_{n+3} = a + b.(n + 3)$

...

To calculate the seasonal indices (S), one index must be assigned for each period. It corresponds to the arithmetic mean of deviations (Y'_k/T_k) for the respective period across the entire data set, where Y'_k is the actual past demand and T_k is the trend value obtained from the trend line for that period, as shown in Equation 5.

$$S = Y'_1/T_1 + Y'_2/T_2 + \cdots + Y'_n/T_n \quad (5)$$

Finally, with the values of *T* and *S* for each period, the forecast corrected for seasonal effects is obtained by multiplying the trend component by the respective seasonal indices. It is worth noting that the deviations (Y'_k/T_k) indicate how influential random fluctuations are in the example at hand. According to Moreira (2012), the use of the average of these past deviations to calculate seasonal indices represents a valid attempt to smooth out random effects.

Choosing the appropriate capacity policy for production management

This is still a qualitative stage. Here, the available options to influence production are considered; that is, management must evaluate the following alternatives:

- Overtime work regime;
- Hiring and firing employees;
- Subcontracting;
- Inventory creation.

The feasibility and limitations assigned to these options represent the capacity policy to adjust production. It is necessary to assess which of these options are viable within the context of each company; for example, whether the company has an overtime work regime and how the designated union regulates this activity, whether the shipyard is located in an area with available and skilled labor for easy hiring, whether there is physical space to store inventory and the associated risks and costs, and whether there are companies capable of providing subcontracted labor in the region.

Thus, at this stage, the inputs are which of these variations in the production system can be adopted for the aggregate planning of the following year. These will be key factors for increasing or decreasing the production rate in each period.

Proposing an optimal aggregate planning alternative for the next year

Existing models that seek to solve the aggregate planning problem can be thought of in two dimensions: those that assume linear cost variation and those that do not, and those that achieve an optimal solution and those that do not. An optimal solution is understood as one that effectively leads to the minimum total production cost given the available production alternatives. The methodology of this work assumes that cost variation is linear and focuses on leading to an optimal solution, i.e., with minimum total production cost.

Model construction

The construction of the optimization model is proposed below in three general steps (definition of constants, definition of constraints, and representation of decision variables and objective function). Finally, a methodology for constructing the optimization algorithm is presented succinctly but with examples.

Step 1: Define constants

To build the model, it is first necessary to assign values to the constants. All constants must have their values defined by the author based on internal investigation and the exchange of information between company departments. The constants and their respective descriptions are presented in Table 3. Readers are advised not to focus yet on the “Assigned Value” column, which will be explained later in Section 4 (Results and Discussion).

Table 3

Constants used in model construction.

Constant	Symbol	Description	Equation	Assigned value
Forecast demand	D_t	Units of products or inputs per period. Corresponds to the trend component (T_t) multiplied by the seasonal component of the period (S_t).	$Y_t = (T_t) \,.\, (S_t)$	$D_1 = 6$, $D_2 = 3$, $D_3 = 6$, $D_4 = 1$, $D_5 = 2$, $D_6 = 3$, $D_7 = 5$, $D_8 = 2$, $D_9 = 2$, $D_{10} = 2$, $D_{11} = 3$, $D_{12} = 2$
Maximum capacity in regular production	R	Maximum number of units of products or inputs produced under regular conditions in a period. Corresponds to the product of the number of employees (F), the workload of the period (CH), and the production rate (T').	$F \times CH \times T'$	7
Maximum capacity for overtime production	H	Maximum number of units of products or inputs produced when there is an overtime regime in a period. The number of overtime hours worked in the period (he) is added to CH.	$F \times (CH + he) \times T'$	9
Maximum capacity for subcontracted production	S	Maximum number of units of products or inputs produced when there is subcontracted production in a period. The number of subcontracted employees (u) is added to F.	$(F + u) \times CH \times T'$	4,3
Regular production at the beginning of the first period	R_0	Production in units of products or inputs at the beginning of the first planning period. The initial number of employees is represented by F_0.	$F_0 \times CH \times T'$	7
Initial inventory (at the beginning of the first period)	I_0	Inventory in units of products or inputs at the beginning of the first planning period. Corresponds to the sum of units produced under normal regime (R_0), overtime (H_0), and subcontracting (S_0) in the initial period, minus the demand (D_0) of this period.	$(R_0 + H_0 + S_0) - D_0$	0
Unit cost of regular production	r	Refers to the cost in reais of producing each unit of product or input.	$\frac{C_{material} + C_{labor} + C_{indirect}}{produced\ units}$	14.000
Unit cost of overtime production	h	Refers to the cost in reais of producing each unit of product or input using an overtime regime.	$\frac{C_{material} + C_{labor} \cdot (1 + \frac{he}{CH} \,.\, 1{,}5) + C_{indirect}}{produced\ units}$	16.000
Unit cost of subcontracted production	s	Refers to the cost in reais of producing each unit of product or input using subcontracting.	$\frac{Total\ subcontracting\ cost}{added\ units}$	-
Cost of adding one unit to regular production through hiring	a	Refers to the cost of hiring enough employees to increase production by one unit. This cost includes the hours of the employees involved in hiring (director, recruiter, HR, accounting, trainer, etc.) and the estimated learning hours.	$\frac{Total\ hiring\ cost}{added\ units}$	1.022
Cost of canceling one unit of regular production through layoffs	c	Refers to the cost of dismissing enough employees to decrease production by one unit. This cost includes severance payments, proportional vacation, vacation bonus (1/3), proportional 13th salary, 40% FGTS, and the hours of employees involved (HR, accounting, director).	$\frac{Total\ layoff\ cost}{canceled\ units}$	11.413
Cost of holding one unit in inventory for one period	i	This cost involves the cost of capital (opportunity cost) and the storage cost (space, insurance,	$\frac{C_{oportunity} + C_{storage}}{units\ in\ inventory}$	600

	fees, losses, material obsolescence, and deterioration) (Moreira, 2012).	

Step 2: Define constraints

The next step is to define the constraints. These are equations or inequalities that link the decision variables and the constants (Table 4). For any period *t*, they are as follows:

Table 4

Constraints used for the construction of the optimization model for each period t.

Constraint	Symbol	Description	Equation/Inequality
Upper bound of regular production	R	Defines the maximum value for regular production in the period	$R_t \leq R$
Upper bound of overtime production	H	Defines the maximum value for overtime production in the period	$H_t \leq H$
Upper bound of subcontracted production	S	Defines the maximum value for subcontracted production in the period	$S_t \leq S$
Composition of regular production in the period	R_t	Regular production in period t is equal to the regular production of the previous period, adding the units produced due to hiring and subtracting the production lost due to layoffs	$R_t = R_{t-1} + A_t - C_t$
Limit of canceling a unit	R	It is not possible to cancel more than the maximum capacity of regular production	$C_t \leq R$
Composition of inventory in the period	I_t	The ending inventory in period t is equal to the ending inventory of the previous period, plus everything produced in period t, minus what was consumed, i.e., demand	$I_t = I_{t-1} + ProdTot_t - D_t$
Definition of total production in the period	ProdTot	Consists of the sum of regular production and overtime production	$ProdTot_t = R_t + H_t$
Non-negativity conditions	> 0	Defines that the variables cannot be negative	$I_t, R_t, H_t, S_t, A_t, C_t > 0$
Integer condition	$\in Z$	Defines that the variables must be integers	$I_t, R_t, H_t, S_t, A_t, C_t \in Z$

Step 3: Represent decision variables and the objective function

The decision variables are the variables whose values are unknown and represent the solution of the linear programming problem (Table 5). Each decision variable must receive as many values as the number of periods considered in aggregate planning. They must be defined in the model, but their values will be assigned by the program. In each period *t*, they are as follows:

Table 5

Decision variables used in the construction of the linear optimization model.

Decision variable	Symbol	Description
Ending inventory	I_t	Represents what remained in inventory in the period
Regular production	R_t	Represents the units of inputs or products produced under regular conditions in that period
Overtime production	H_t	Represents the units of inputs or products produced under overtime in that period
Subcontracted production	S_t	Represents the units of inputs or products produced by subcontracting in that period
Units added through hiring	A_t	Represents the amount of input or product added to production due to employees hired in that period
Units canceled through layoffs	C_t	Represents the amount of input or product reduced from production due to employees dismissed in that period

The objective function (Table 6) is composed of the costs and decision variables; it aims to minimize the total production cost for the periods considered. The expression $(rR_t + hH_t + sS_t + aA_t + cC_t + iI_t)$ represents the production cost in period t, considering the options of regular production, overtime, subcontracting, inventory, and the increase/decrease of regular production via hiring/layoffs. It must be represented in the program so that its final value is obtained as the solution.

Table 6

Representation of the objective function.

	Symbol	Description
Objective function	$\sum_{t=1}^{n}(rR_t + hH_t + sS_t + aA_t + cC_t + iI_t)$	Represents the sum of production costs over the periods. It must be minimized

Optimization algorithm

To facilitate replication of the model, this section presents an algorithm for the optimization model in classical mathematical language, as shown in Table 7. For the construction of the aggregate planning optimization program, one begins by defining the constants and representing the variables. Then, the constraints are defined, and finally, the minimization of the objective function is requested. As a result, the values of the variables for each period that minimize the objective function will be obtained.

Several software tools exist for building and simulating optimization models, such as LINGO, SOLVER, and CPLEX, each with its own capacities and specific uses. It should be noted that these tools do not contain ready-made optimization models for the problem addressed. They are the only graphical interfaces that facilitate the construction and simulation of optimization models.

Table 7

Algorithm for the optimization model in classical mathematical language.

1. Definition of Constants:
H: Maximum capacity of overtime production. R_0: Initial regular production. I_0: Initial inventory. r: Cost of regular production. h: Cost of overtime production. a: Cost of adding one unit to regular production through hiring. c: Cost of canceling one unit of regular production through layoffs. s: Cost of adding one unit to regular production through subcontracting. i: Cost of holding one unit in inventory during a period. D_i: Demand in period i. R: Maximum capacity of regular production.
2. Representation of variables:
A_i: Units added through hiring in period i. C_i: Units canceled through layoffs in period i. S_i: Units added through subcontracting in period i. I_i: Inventory in period i.
3. Representation of constraints:
$0 \leq R_i \leq R$: Maximum capacity of regular production and overtime. $0 \leq H_i \leq H$: Maximum capacity of overtime production in period i. $0 \leq C_i \leq R$: It is not possible to cancel more than the maximum capacity of regular production. R_i= $R_{(i-1)} + S_i - A_i - C_i$: Regular production in period i. $ProdTot_i = R_i + H_i$: Total production in period i. $I_i = I_i - 1 + ProdTot_i - D_i$: Inventory in period i.
4. Definition of the Objective Function:
$Cost = \sum_{i=1}^{n} (rR_i + hH_i + sS_i + aA_i + cC_i + iI_i)$
5. Minimization:
Minimize the objective function Cost.

Results and Discussion

This section presents the results obtained through the application of the proposed methodology in a real case, namely a nautical shipyard located in the state of Santa Catarina with 10 employees in production. The shipyard's main product is a small sailboat, whose main dimensions are shown in Table 8, designed for both regatta competitions and sailing lessons. The model's name is not disclosed for confidentiality reasons. Since the sailboat is the shipyard's main product, it was used as the reference unit for the aggregate planning calculations. This application was carried out in December 2023 to generate results for the planning period from January to December 2024.

Table 8

Main dimensions of the sailboat addressed in this study.

Beam	1.66m
Length	4.16m
Draft	0.18m
Depth	0.52m

Measuring capacity

The measure chosen to represent the shipyard's capacity was the number of units produced, i.e., the number of boats. The selected period was one month. Thus, capacity is expressed in boats per month.

The limiting resource for boat construction at the shipyard, that is, the factor that constrains its productive capacity, is the number of molds available (equipment). Its production rate (T') can be determined using Equation 1.

A total of seven boats can be produced in one month, and the elapsed time corresponds to the product of the number of molds (1) by the working hours in the period (174 h/month). Once the production rate is defined, capacity can be calculated using Equations 6 and 7 below.

$$T' = \frac{Total\ produced}{Elapsed\ time} = \frac{7\ boats}{1\ mold * 174h} = 0{,}04\ boats/h \quad (6)$$

$$Capacidade = 174h \times 0{,}04\ boats/h = 7\ boats/month \quad (7)$$

Although the production capacity meets the average annual demand, the model shows that there are significant monthly variations in demand (see Section 3.2 and Table 9), which may lead to idle capacity in some months and overload in others. Thus, the aggregate planning model enables production adjustments to minimize operating costs and avoid inefficient decisions, such as maintaining high inventory levels or resorting to emergency production at higher costs.

Therefore, even though the average capacity may appear sufficient, demand fluctuations and seasonality require structured planning to reduce the total operating cost throughout the year.

Forecasting demand

To forecast the company's demand in 2024, the Time Series Decomposition method (Section 3.2) was adopted. This model was chosen because it requires input data that can be easily obtained from the company, namely, its historical demand.

The company has records of its sales from January 2019 to December 2023, as shown in Table 9 and Figure 3. Both present the original data and the trend line. Although several functions could be tested for the trend line, a straight line was chosen because it allows a clearer visualization of the seasonal effect. The line consistently lies above the actual values in low-demand months and below them in high-demand months.

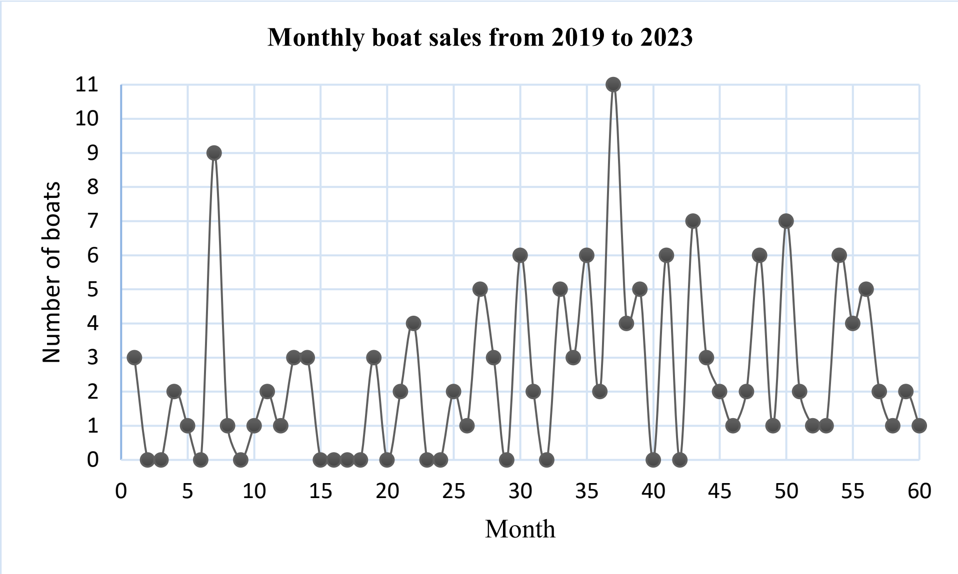
Table 9

Boats sold from January 2019 to December 2023.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2019	3	0	0	2	1	0	9	1	0	1	2	1	20
2020	3	3	0	0	0	0	3	0	2	4	0	0	15
2021	2	1	5	3	0	6	2	0	5	3	6	2	35
2022	11	4	5	0	6	0	7	3	2	1	2	6	47
2023	1	7	2	1	1	6	4	5	2	1	2	1	33

Figure 3

Monthly boat sales from 2019 to 2023.



To determine the trend line, the time values *t* were considered on a scale in which the first month of 2019 was taken as *t = 0*, the second as *t = 1*, and so forth. The last data point corresponds to December 2023, when *t = 59*. Letting *y* represent the forecast given by the trend line and *t* the time, its form is represented in Equation 8.

$$\hat{Y} = 0{,}0076t + 3{,}0752 \quad (8)$$

Table 10

Values for the calculation of the coefficient of determination.

X	Y	Ŷ	(Y-Y̲)	(Y-Y̲)²	(Ŷ-Y̲)	(Ŷ-Y̲)²
0	3	3.075	0.500	0.250	0.575	0,331
1	0	3.083	-2.500	6.250	0.583	0,340
2	0	3.090	-2.500	6.250	0.590	0,349
3	2	3.098	-0.500	0.250	0.598	0,358
4	1	3.106	-1.500	2.250	0.606	0,367
5	0	3.113	-2.500	6.250	0.613	0,376
6	9	3.121	6.500	42.250	0.621	0,385
7	1	3.128	-1.500	2.250	0.628	0,395
8	0	3.136	-2.500	6.250	0.636	0,404
9	1	3.144	-1.500	2.250	0.644	0,414
10	2	3.151	-0.500	0.250	0.651	0,424

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11	1	3.159	-1.500	2.250	0.659	0,434
12	3	3.166	0.500	0.250	0.666	0,444
13	3	3.174	0.500	0.250	0.674	0,454
14	0	3.182	-2.500	6.250	0.682	0,465
15	0	3.189	-2.500	6.250	0.689	0,475
16	0	3.197	-2.500	6.250	0.697	0,486
17	0	3.204	-2.500	6.250	0.704	0,496
18	3	3.212	0.500	0.250	0.712	0,507
19	0	3.220	-2.500	6.250	0.720	0,518
20	2	3.227	-0.500	0.250	0.727	0,529
21	4	3.235	1.500	2.250	0.735	0,540
22	0	3.242	-2.500	6.250	0.742	0,551
23	0	3.250	-2.500	6.250	0.750	0,563
24	2	3.258	-0.500	0.250	0.758	0,574
25	1	3.265	-1.500	2.250	0.765	0,586
26	5	3.273	2.500	6.250	0.773	0,597
27	3	3.280	0.500	0.250	0.780	0,609
28	0	3.288	-2.500	6.250	0.788	0,621
29	6	3.296	3.500	12.250	0.796	0,633
30	2	3.303	-0.500	0.250	0.803	0,645
31	0	3.311	-2.500	6.250	0.811	0,657
32	5	3.318	2.500	6.250	0.818	0,670
33	3	3.326	0.500	0.250	0.826	0,682
34	6	3.334	3.500	12.250	0.834	0,695
35	2	3.341	-0.500	0.250	0.841	0,708
36	11	3.349	8.500	72.250	0.849	0,720
37	4	3.356	1.500	2.250	0.856	0,733
38	5	3.364	2.500	6.250	0.864	0,746
39	0	3.372	-2.500	6.250	0.872	0,760
40	6	3.379	3.500	12.250	0.879	0,773
41	0	3.387	-2.500	6.250	0.887	0,786
42	7	3.394	4.500	20.250	0.894	0,800
43	3	3.402	0.500	0.250	0.902	0,814
44	2	3.410	-0.500	0.250	0.910	0,827
45	1	3.417	-1.500	2.250	0.917	0,841
46	2	3.425	-0.500	0.250	0.925	0,855
47	6	3.432	3.500	12.250	0.932	0,869
48	1	3.440	-1.500	2.250	0.940	0,884
49	7	3.448	4.500	20.250	0.948	0,898

50	2	3.455	-0.500	0.250	0.955	0,912
51	1	3.463	-1.500	2.250	0.963	0,927
52	1	3.470	-1.500	2.250	0.970	0,942
53	6	3.478	3.500	12.250	0.978	0,956
54	4	3.486	1.500	2.250	0.986	0,971
55	5	3.493	2.500	6.250	0.993	0,986
56	2	3.501	-0.500	0.250	1.001	1,002
57	1	3.508	-1.500	2.250	1.008	1,017
58	2	3.516	-0.500	0.250	1.016	1,032
59	1	3.524	-1.500	2.250	1.024	1,048
	150	$\underline{Y}$ = 150/60 = 2.5		1305746		39.382

Applying the values obtained in Table 10 to the equation in Table 2, the coefficient of determination was found to be $r^2 = 0.106$. This means that 11% of the variation in *y* is explained by the variation in *t*, while the remaining 89% of the variation is due to unknown factors. The value of r^2 indicates that the immediate fit has a low correlation. Additionally, the trend component values for 2024, calculated according to Equation 8, are shown in Figure 4.

Figure 4

Calculation of the trend component for future periods.

Month 1 (t = 60): $y_{60} = T_{60} = 0{,}0076(60)$ + 3,0752 = 3.531

Month 2 (t = 61): $y_{61} = T_{61} = 0.0076(61)$ + 3.0752 = 3.539

Month 3 (t = 62): $y_{62} = T_{62} = 0.0076(62)$ + 3.0752 = 3.546

Month 4 (t = 63): $y_{63} = T_{63} = 0.0076(63)$ + 3.0752 = 3.544

Month 5 (t = 64): $y_{64} = T_{64} = 0.0076(64)$ + 3.0752 = 3.561

Month 6 (t = 65): $y_{65} = T_{65} = 0.0076(65)$ + 3.0752 = 3.569

Month 7 (t = 66): $y_{66} = T_{66} = 0.0076(66)$ + 3.0752 = 3.577

Month 8 (t = 67): $y_{67} = T_{67} = 0.0076(67)$ + 3.0752 = 3.584

Month 9 (t = 68): $y_{68} = T_{68} = 0.0076(68)$ + 3.0752 = 3.592

Month 10 (t = 69): $y_{69} = T_{69} = 0.0076(69)$ + 3.0752 = 3.600

Month 11 (t = 70): $y_{70} = T_{70} = 0.0076(70)$ + 3.0752 = 3.607

Month 12 (t = 71): $y_{71} = T_{71} = 0.0076(71)$ + 3.0752 = 3.615

To define the seasonal indices, Figure 4 is used, with its values represented in Table 11. For each month, there are five past observations (from 2019 to 2023), which allows the calculation of each seasonal index as the average of the deviations previously observed between the actual value and the trend component.

Table 11

Calculation of seasonal indices.

Period	Actual demand (Y)	Trend T_k	Y/T_k	Period	Actual demand (Y)	Trend T_k	Y/T_k
1	3	3.083	0.973	31	2	3.311	0.604
2	0	3.090	0.000	32	0	3.318	0.000
3	0	3.098	0.000	33	5	3.326	1.503
4	2	3.106	0.644	34	3	3.334	0.900
5	1	3.113	0.321	35	6	3.341	1.796
6	0	3.121	0.000	36	2	3.349	0.597
7	9	3.128	2.877	37	11	3.356	3.277
8	1	3.136	0.319	38	4	3.364	1.189
9	0	3.144	0.000	39	5	3.372	1.483
10	1	3.151	0.317	40	0	3.379	0.000
11	2	3.159	0.633	41	6	3.387	1.772
12	1	3.166	0.316	42	0	3.394	0.000
13	3	3.174	0.945	43	7	3.402	2.058
14	3	3.182	0.943	44	3	3.410	0.880
15	0	3.189	0.000	45	2	3.417	0.585
16	0	3.197	0.000	46	1	3.425	0.292
17	0	3.204	0.000	47	2	3.432	0.583
18	0	3.212	0.000	48	6	3.440	1.744
19	3	3.220	0.932	49	1	3.448	0.290
20	0	3.227	0.000	50	7	3.455	2.026
21	2	3.235	0.618	51	2	3.463	0.578
22	4	3.242	1.234	52	1	3.470	0.288
23	0	3.250	0.000	53	1	3.478	0.288
24	0	3.258	0.000	54	6	3.486	1.721
25	2	3.265	0.613	55	4	3.493	1.145
26	1	3.273	0.306	56	5	3.501	1.428
27	5	3.280	1.524	57	2	3.508	0.570
28	3	3.288	0.912	58	1	3.516	0.284
29	0	3.296	0.000	59	2	3.524	0.568
30	6	3.303	1.816	60	1	3.531	0.283

The deviations Y/T_k for January correspond to periods 1, 13, 25, 37, and 49. According to Equation 5, by taking the arithmetic mean of these values, we obtain S_n, that is, the seasonal index for the first month S_1. In the same way, the indices from S_1 to S_{12} were calculated in Table 12.

Table 12

Calculation of seasonal indices.

	n	2019	2020	2021	2022	2023	Average (S_n)
January	1	0.973	0.945	3.265	3.277	0.290	1.750
February	2	0.000	0.943	0.306	1.189	2.026	0.893
March	3	0.000	0.000	1.524	1.483	0.578	0.717
April	4	0.644	0.000	0.912	0.000	0.288	0.369
May	5	0.321	0.000	0.000	1.772	0.288	0.476
June	6	0.000	0.000	1.816	0.000	1.721	0.708
July	7	2.877	0.932	0.604	2.058	1.145	1.523
August	8	0.319	0.000	0.000	0.880	1.428	0.525
September	9	0.000	0.618	1.503	0.585	0.570	0.655
October	10	0.317	1.234	0.900	0.292	0.284	0.605
November	11	0.633	0.000	1.796	0.583	0.568	0.716
December	12	0.316	0.000	0.597	1.744	0.283	0.588

To obtain the forecasts adjusted for the seasonal effect for the 12 months of 2024, the trend components are simply multiplied by their respective seasonal indices (Table 1). The calculation results are shown in Table 13.

Table 13

Calculation of forecasts adjusted by the seasonal index.

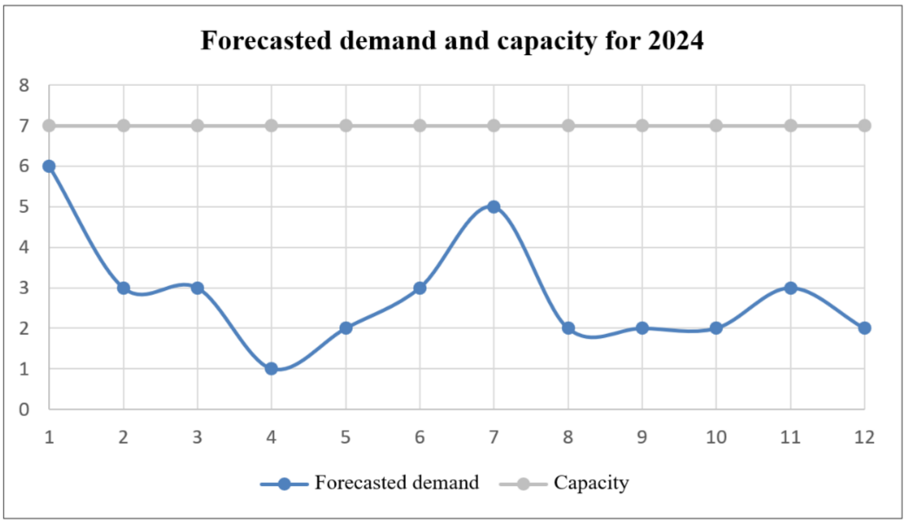
	T_k	S_n	Adjusted forecast
January 2024	3.531	1.750	6
February 2024	3.539	0.893	3
March 2024	3.546	0.717	3
April 2024	3.554	0.369	1
May 2024	3.562	0.476	2
June 2024	3.569	0.708	3
July 2024	3.577	1.523	5
August 2024	3.584	0.525	2

September 2024	3.592	0.655	2
October 2024	3.600	0.605	2
November 2024	3.607	0.716	3
December 2024	3.615	0.588	2

As a final observation, the deviations Y/T_k over the years and within each month are considerable. This inconsistency in the relationship between actual demand and the trend component for each month indicates that random fluctuations significantly affect the company in question. The calculation of the seasonal index through the average of past deviations represents a valid attempt to smooth these random effects. A simplified representation of the demand for the following year and the company's capacity can be seen in Figure 5.

Figure 5

Graph showing the demand forecast for the study year.



Choosing the appropriate capacity policy for production management

Among the alternatives available to influence production, the model aimed to represent the options the company already employs. The following practices are already common in the company and will therefore be considered:

- Overtime.
- Hiring and firing of employees.
- Finished goods inventory.

Although inventory generation occurs less frequently, it is considered because the factory has the space and infrastructure available to store finished boats. The option of subcontracting will not be considered in this company's calculations, as the manufacturing process (specifically, the boat lamination plan) is confidential, and management does not wish to share it with third parties to avoid competition. Additionally, there is no available workforce in the region to perform this type of service.

Proposing the optimal aggregate planning alternative

For the case in question, the company's Aggregate Planning should be carried out over a total horizon of 12 months. To construct the linear optimization model for Aggregate Planning, the methods presented in Section 3 are followed. The "Assigned Value" column in Table 3 corresponds to Step 1 (Definition of Constants), Table 4 corresponds to Step 2 (Definition of Constraints), and Tables 5 and 6 correspond to Step 3 (Representation of Decision Variables and Objective Function).

The cost values used in the model were obtained from information provided directly by the company through interviews with the Finance, HR, Engineering, and Logistics departments. These values represent estimated averages based on historical data and projections provided by the respective areas.

The regular production cost (r) was calculated as the sum of the average costs of materials, direct labor, and manufacturing overhead, divided by the number of units produced monthly. The overtime production cost (h) incorporated a 50% premium over the base hourly rate, according to current labor legislation and the company's payment practices. Hiring (a) and firing (c) costs were determined based on internal simulations performed by HR, considering labor charges, training time, and administrative procedures. Inventory cost (i) was based on estimates of capital opportunity cost and operational storage costs reported by the logistics department. A description of each cost with its respective equation can be found in Table 3.

Optimization Algorithm

After all these values were properly entered as inputs into the optimization algorithm, the simulation was performed, and the output consists of the Aggregate Planning results shown in Table 14, representing a minimum production cost of R$ 500.213,00 (Table 6). The LINGO software was used to simulate the model. The file containing the algorithm can be downloaded through the reference (Lemos, 2024).

Table 14

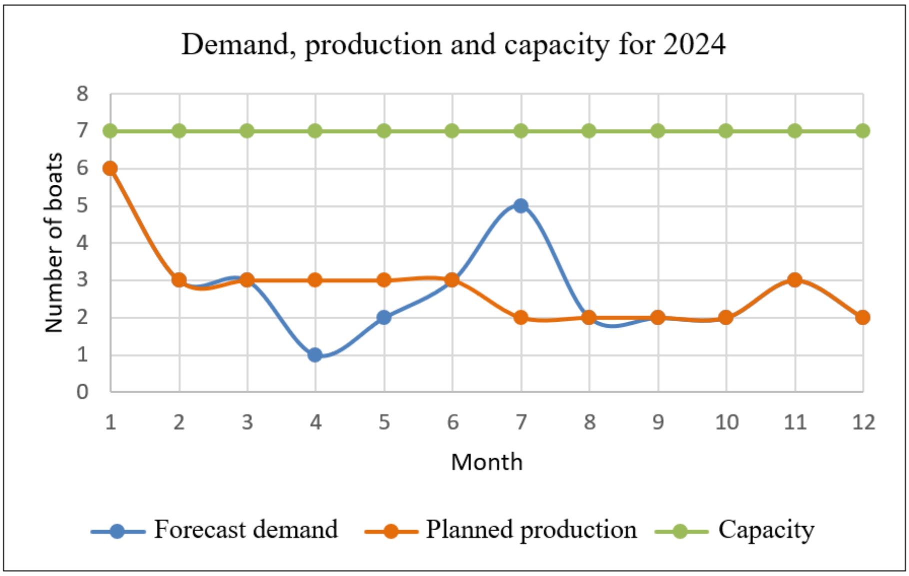
Optimal result of the company's linear programming aggregate planning.

	Period											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Demand	6	3	3	1	2	3	5	2	2	2	3	2
Initial inventory	0	0	0	0	2	3	3	0	0	0	0	0
Final inventory	0	0	0	2	3	3	0	0	0	0	0	0
Initial number of employees	5	5	5	5	5	5	5	4	4	4	4	4
Hires	0	0	0	0	0	0	0	0	0	0	0	0
Firings	0	0	0	0	0	0	1	0	0	0	0	0
Final number of employees	5	5	5	5	5	5	4	4	4	4	4	4
Regular production	3	3	3	3	3	3	2	2	2	2	2	2
Overtime production	3	0	0	0	0	0	0	0	0	0	1	0
Subcontracted production	-	-	-	-	-	-	-	-	-	-	-	-
Total production	6	3	3	3	3	3	2	2	2	2	3	2

The production obtained in the aggregate planning calculation, along with the forecasted demand and the company's capacity for the year, can be seen in Figure 6. It is possible to observe that the factory will be operating below its capacity during the period.

Figure 6

Representation of production forecasted demand, and company capacity for the study year.



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It is important to highlight that capacity is always greater than both forecasted demand and planned production. This means there will always be idle physical space and machinery, but not necessarily idle human resources, which is the focus of aggregate planning in this study. The company's human resources will be adjusted through hiring, layoffs, and overtime work to minimize costs. It is worth noting that in certain months (i.e., July, August, September, October, and December), labor idleness was observed, indicating that it is sometimes more cost-effective to maintain idle labor than to lay off and rehire employees.

Methodology discussion

The methodology employed proved feasible in a real-world scenario, demonstrating its potential usefulness for the industry in question. The time required to apply this methodology in a small shipyard (with fewer than 20 employees) can be estimated at 1 to 2 weeks. This methodology could even be implemented as a consulting service for industries in the sector due to its multiple benefits. Its implementation is recommended for batch production systems, but is not suitable for shipyards producing exclusive, project-based vessels.

While this methodology was developed for small shipyards, it can also be adapted for other manufacturing sectors. However, some adjustments may be necessary, such as modifying the number of periods for goods with significantly longer or shorter production times.

It is important to emphasize that the optimization model presented in this study is deterministic, meaning it assumes all input variables, including forecasted demand, are known with certainty at the time of decision-making. However, it is recognized that demand forecasting involves uncertainty, particularly when based on time series. To mitigate the effects of this uncertainty and enable realistic model operation, the common practice of using average forecasted values as inputs for the deterministic model is adopted here. In future versions and more robust applications, the model could be adapted to incorporate stochastic approaches that explicitly address demand-related uncertainty.

Additionally, alternative methods for demand estimation can be employed. For instance, a company may lack significant historical demand data or prefer a more qualitative approach. The choice of a different demand estimation method does not interfere with the execution of the remaining steps in the methodology.

The proposed model has the following limitations:

- The model is deterministic and does not account for variability and uncertainty in the variables;
- Some computational tools for building and simulating optimization models are proprietary (e.g., LINGO and CPLEX). For modeling in LINGO, a student license was requested from the software manufacturer via email, as the calculations for the following year required the creation of 73 variables, while the free demo version allows a maximum of 40 variables;
- The results of aggregate planning are based on demand forecasts, which inherently involve uncertainty. To address this issue, adjustments to the aggregate planning model inputs can be made as needed;
- The greater the availability of historical demand data, the higher the accuracy of demand forecasting. Consequently, aggregate planning may face challenges in newly established companies with limited demand history.

For future work, the development of a probabilistic model is proposed by incorporating stochastic modeling and simulation techniques (e.g., Monte Carlo) that consider variability and uncertainty in the variables. Additionally, given the financial constraints imposed by proprietary tools, exploring open-source alternatives is recommended. For example, optimization libraries in programming languages such as Python offer numerous functionalities without additional costs.

Regarding the uncertainty in aggregate planning results due to demand forecasts, it is recommended that future work implement strategies for continuous model review, incorporating frequent adjustments based on real-world data. Furthermore, for companies with limited demand history or newly established businesses, it is suggested that future research explore demand forecasting methods based on external data, such as market analysis and industry trends.

Discussion of results

The practical application of the methodology was illustrated through its implementation in the development of aggregate planning for a nautical shipyard in Santa Catarina. In this specific case, the following most relevant results were obtained for production in the following year:

- In January, it will be necessary to produce three boats under an overtime regime to meet the forecasted demand for the period;
- For three months of the year (April, May, and June), it is planned to maintain finished products in inventory (2, 3, and 3 boats, respectively). This indicates that the company will need to have physical space available for storing up to three boats;
- In July, the layoff of one employee is planned. This indicates, for example, that the production manager will have more time to evaluate which production sector should have its number of employees reduced; furthermore, the financial sector can plan cash flow for severance payments and indemnities;
- Based on the estimate of this cost, the shipyard management can perform more effective financial planning for the following year, including resource allocation, price setting, and improved decision-making regarding future planning. It also assists in decisions about expansion, investment in new technologies, contractual negotiations, and risk management. Regardless of the plan, it should not be considered a rule to be strictly followed. Throughout the year, the execution of the plan should be monitored and adjusted if necessary. The same methodology can be used for replanning the remaining periods.

As limitations, it is worth noting that:

- The results do not specify details about the exact functions of the employees to be hired or laid off during the planned periods, leaving it to the production manager to apply their knowledge in making these decisions.

As proposals for future applications of aggregate planning for 2025 in this shipyard, it is suggested to update the product cost information to verify whether labor, raw material, and indirect costs have increased or decreased. It is also recommended to review and update other data serving as input to the optimization model, such as production rate, inventory cost, and capacity calculation. In addition, the demand database should continue to be updated to enable more accurate forecasting.

Conclusion

The methodology proposed in this study represents a significant advancement toward technological improvement in the Brazilian nautical industry. Although the sector has grown in importance in Brazil, production planning and control in nautical shipyards still lack technical knowledge. This work offers a promising approach to addressing this gap, contributing to the efficiency and competitiveness of the sector.

As the main result, this article presents a generic methodology that can be applied in any nautical shipyard, especially those with fewer than 20 employees, for optimized aggregate planning. The methodology provides, as its principal outcome, an optimal planning table based on the criterion of minimizing the total production cost for monthly production in the following year, and it predicts the total production cost. Its main advantage is that it allows shipyard management to plan resources—human, financial, and machinery—more effectively for the next year. Its main limitation is that it relies on the demand forecast for the following year, which involves uncertainties.

The methodology arose from a practical need, standing out because it was driven by real field demands rather than originating from theory, as is common in many academic studies. This practical, application-oriented approach provides a clearer understanding of the theory, making it more didactic and accessible to readers. The application of the methodology in a real case not only facilitates understanding but also demonstrates its feasibility and practical relevance. In the specific context of a shipyard, the implementation of aggregate planning resulted in more solid guidance for meeting market demands in a competitive and effective manner. This means that the company is better prepared to deal with fluctuations in demand, optimizing its resources and ensuring greater operational efficiency.

For future work, it is suggested to explore the adoption of stochastic modeling techniques to incorporate variability and uncertainty into the variables of the proposed model, which is currently deterministic. Additionally, it is recommended to develop a methodology that contemplates more options for demand forecasting calculations, allowing the reader to choose the most appropriate method for their case.

REFERENCES

ACOBAR. (2012). *Indústria náutica brasileira: fatos e números 2012*. www.acobar.org.br

Associação Brasileira da Classe Dingue. (2025). História do Dingue e da Classe Dingue no Brasil. Classe Dingue. https://classedingue.com.br/historia/

Aurélio Schmidt, M., Everling, M., & Shibata Santos, A. (2017). Materiais e processos na indústria náutica: o delineamento de um desenvolvimento projetual. *DATJournal*, *2*(2), 34–51.

Barbosa, E. G., Duarte, H. O., Melo, S., & Bonnano, J. V. (2016). Project management methodology for boat designing: the case of an as-built project of a 33-foot boat in a Brazilian shipyard. *Trans RINA*, *158*, 1–13. https://doi.org/10.3940/rina.ijme.2016.a2

Cordeiro, D. R., Cordeiro, D. C., Rocha, R. P., & Morais, M. de F. (2015). Modelagem Matemática para o Planejamento Agregado da Produção: Estratégia de Produção Constante e Estratégia de Acompanhamento da Demanda. *IX Encontro de Engenharia de Produção Agroindustrial*, 1–12.

DPC. (2023). NORMAM-211/DPC Normas de autoridade marítima para atividades de esporte e recreio. *Marinha do Brasil, Diretoria de Portos e Costas (DPC)*, 1–227.

Filho, O. S. S., Carvalho, M. F. H. C., Henrique, M. M., & Fernandes, C. A. (1995). Planejamento agregado da produção ótimo com limite mínimo de estoque influenciado pelas incertezas de demanda. *Gestão & Produção*, *2*(1), 8–24.

Gassen, G., Graciolli, O. D., Chiwiacowsky, L. D., & Mesquita, A. (2019). Proposta de um modelo de programação linear para otimização do planejamento agregado de produção de brocas para empresa multinacional. *Revista Científica Eletrônica de Engenharia de Produção*, *19*(1), 21–43.

Jesus, M. L. (2014). *Planejamento agregado de produção em uma indústria de manufatura de equipamentos: produção versus demanda* [Monograph]. Universidade Federal de Minas Gerais.

Júnior, E. G. B. (2018). *Gestão de tempo e recursos no projeto de embarcaçōs de esporte e recreio: metodologia proposta e exemplo de aplicação* [Undergraduate Thesis]. Universidade Federal de Pernambuco.

Junqueira, R. de Á. R., & Morabito, R. (2006). Um modelo de otimização linear para o planejamento agregado da produção e logística de sementes de milho. *Produção*, *16*(3), 510–525.

Lemos, C. Z. de M. (2024, abril 21). *Algoritmo de otimização do Planejamento Agregado no programa LINGO*. https://l1nk.dev/iKEl2

Moreira, D. A. (2012). *Administração da produção e operações* (2º ed). Cengage Learning.

Munhoz, J. R., & Morabito, R. (2010). Otimização no planejamento agregado de produção em indústrias de processamento de suco concentrado congelado de laranja. *Gestão da produção*, *17*(3), 465–481.

Oliveira, J. P. N. de. (2014). Avaliação do Nível de Maturidade em Gerenciamento de Projetos no Setor de Engenharia de Projetos de um Estaleiro de Grande Porte no Nordeste Brasileiro. *Revista de Gestão e Projetos*, *5*(3), 01–13. https://doi.org/10.5585/gep.v5i3.257

Oliveira, L. H. S. (2011). *Planejamento agregado da produção: um estudo de caso na indústria têxtil*. Universidade de São Paulo.

Oliveira, V. A. (2011). *Programação da produção em um estaleiro náutico* [Master's Dissertation]. Universidade Tecnológica Federal do Paraná.

Paiva, R. P. O. de, & Morabito, R. (2007). Um modelo de otimização para o planejamento agregado da produção em usinas de açúcar e álcool. *Gestão de produção*, *14*(1), 25–41.

Pasa, V. C., Olivo, C. J., & Radharamanan, R. (2017, janeiro 12). *Maximização do lucro de uma empresa através do planejamento agregado: uma nova proposta*. 1–8. https://www.researchgate.net/publication/266267818

Prado, D. (2010). *Maturidade em Gerenciamento de Projetos* (2º ed, Vol. 7). INDG.

Slack, N., Chambers, S., Harland, C., Harrison, A., & Johnston, R. (2010). *Administração da produção Edição compacta* (1º ed). Atlas.