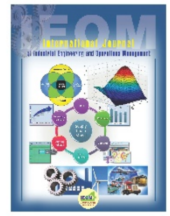
International Journal of Industrial Engineering and Operations Management (IJIEOM)
Volume. 1, No. 2, pp. 138-153, December 2019

IEOM Society International

International Journal of Industrial Engineering and Operations Management (IJIEOM)

Volume 1, No. 2, December 2019
pp. 138 - 153



Dual Approach to the Harmonized Model between Inventory Reduction and Heijunka (Production Leveling) based on the Minimum Average-energy Principle

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ABSTRACT

A major issue in manufacturing is the balance between inventory reduction and heijunka (i.e., production leveling). To address this issue in aggregate production planning, linear programming models that consider many factors and use "exponential smoothing" as an approximate leveling method have been mainly studied. However, this methodology has problems that may limit its use as an optimal solution approximate method, and impair the timeliness required for aggregate production planning by the complexity of these models. To solve this issue, we have been developing harmonized models to balance between lowering the inventory management energy and increasing the heijunka entropy, based on demand and inventory quantities as simple optimization models. In this study, we develop a dual approach to the previously proposed model to maximize the heijunka entropy and propose a new model to minimize the inventory management energy based on the "minimum average-energy principle." We show that the proposed model's inventory state is lower than that of traditional exponential smoothing through numerical experiments. This study, therefore, theoretically enables a new optimal solution to the harmonized (balancing) problem, based on the concept of entropy and energy, and practically enables aggregate production planning in a timely and simple manner.

ARTICLE INFO

Received
April 17, 2019
Received in revised form
June 13, 2019
Accepted
September 10, 2019

KEYWORDS

Aggregate Production Planning, Maximum Entropy Principle, Smoothing Coefficient, Heijunka Entropy, Inventory Management Energy

1. Introduction

The manufacturing industry has experienced major changes in its market environment in recent years, and manufacturing and supplying products at low cost in response to changing demand, without missing sales opportunities, has become a significant issue. Therefore, finding a balance between "agile production," which refers to allowing the supply of products to the market in a timely manner for inventory reduction, and "stable (leveled) production," which is aimed at reducing manufacturing costs, is a difficult problem in production and inventory management. In production planning—especially aggregate production planning, this issue is treated as a production quantity planning problem that must be solved for each production quantity per unit period (e.g., per month) throughout the planning horizon (Kuroda 1994), for which linear programming methods offer a typical solution (Kuroda 1994, Buffa and Miller 1979). Under such an environment, the just-in-time (JIT) production system (or the Toyota production system) has been introduced, mainly in assembly-type manufacturing industries. The core concept of the JIT system is "heijunka (production leveling)" (Monden 2011, Just-in-time production system study group 2004). In aggregate production planning, studies have begun to incorporate the concept of heijunka into linear programming models, mainly using "exponential smoothing", but the number of such studies is still low (Tamura and Kojima 2013).

Exponential smoothing is a convenient method that involves easy—but only approximate—leveling at a fixed ratio according to the indicated smoothing coefficient. If optimal leveling can be performed under the indicated state, more effective production planning will be possible. Furthermore, in linear programming models, under the stochastic but stationary demand experiencing mainly irregular (random) fluctuations, the optimal production quantities are determined based on various elements and data, such as resources, costs, and benefits. Consequently, the models become increasingly complicated and their computation time increases, which may impair the timeliness required to implement aggregate production planning (Bowersox et al. 2010). In particular, for products with large fluctuations in demand, there are more elements to be considered and the relationships among the elements become more complex, so planning becomes more problematic under this approach.

In order to solve the problems regarding aggregate production planning of seasonal products with large seasonal fluctuations, we have worked on the development of new methods to simply maximize the leveling under the deterministic demand involving large seasonal fluctuations, by paying attention to the demand, production, and inventory quantities of the basic planning elements. Accordingly, we have considered that the balancing problem—of agile production (inventory reduction) in response to changing sales and leveled production (heijunka) in pursuit of efficiency—is the maximization problem of the heijunka state (entropy) for a constant inventory level (average-energy), and we have narrowed down the elements and data to be used in this model; we previously proposed a harmonized model between inventory reduction and heijunka (Kurihara and Yamashita 2013), herein referred to as "the base model", which was formulated based on the "maximum entropy principle" (Jaynes 1957).

The base model (Kurihara and Yamashita 2013) can optimize (maximize) the heijunka state under a constant inventory level, but it cannot optimize (minimize) the inventory state for the reverse condition, i.e., a constant heijunka level. Therefore, in this study, we propose a new model that can minimize the inventory state under a constant heijunka level (according to the production capacity of existing facilities and workforce). Using the concept of the base model that simply captures the essence of the harmony problem, we develop a new dual approach to exchange the objective function and the constraint for the problem setting of the base model based on the "maximum entropy principle", and propose a new harmonized model between inventory reduction and "heijunka" (production leveling), based on the "minimum average-energy principle" (Fukao 1987).

Thus, in this harmonized model considering inventory reduction and heijunka, the inventory state cannot only be determined under the indicated heijunka level through the smoothing coefficient—as do linear programming models using exponential smoothing (Tamura and Ohno 2013, Sato et al. 2005, Tsubone and Tanaka 1990), but also minimized analytically based on the minimum average-energy principle, unlike exponential smoothing. By taking advantage of the ease of calculation and solution optimization, the proposed model can be applied to aggregate production planning, especially production-sales-inventory planning and the production planning of small and medium-sized enterprises (SMEs).

Moreover, in order to verify the validity and effectiveness of the proposed model, we provide simple numerical examples based on the sales results of domestic home air-conditioners (a typical seasonal product in Japan), analyze the proposed model from the viewpoints of functions and duality with respect to the base model, and provide a comparison with the exponential smoothing approach used in previous studies, based on the results of the numerical examples.

2. Literature overview

In general, manufacturing systems can be classified into two types: assembly-type and process-type systems. The industry manufacturing air-conditioners, which are considered as a typical seasonal product in this study, is classified as an assembly-type manufacturing industry, a representative of which is also the automobile manufacturing industry. A typical production management system in the Japanese automobile manufacturing industry is the JIT system, the key feature of which is "synchronized production," which in turn requires "heijunka" (production leveling). Monden (2011) points out two concepts about heijunka as applied to the JIT system, namely "leveling of total amount" and "leveling of quantity by item". The former concept is used to minimize the variation of the total production amount (especially peaks and valleys in production) for each period by equalizing the production quantity of all the items per period as much as possible. The latter concept was developed based on the concept of leveling the total amount considering diversification of market needs, and it minimizes the variation of the item-by-item production quantities by equalizing their production quantities per period as much as possible.

In general, production planning systems in manufacturing companies have a hierarchical structure, and can be divided (from top to bottom) into aggregate production planning (long-term planning), master production scheduling (medium-term planning), and production sequencing (short-term scheduling) (Fleischmann and Meyr 2003, Miller 2002, Hax and Meal 1975). Typical problems in production planning include "production quantity planning problems" to determine the production quantity (including inventory quantity) in the planning horizon, "load planning problems" concerned with the estimation of workload per production facility, leveling of workload, and adjustment of production capacity, and "scheduling problems" to determine the order of the assembly or processing work (Kuroda 1994). These production planning problems are treated as the main issues in the abovementioned production planning, i.e., aggregate production planning for production quantity planning problems, master production scheduling for load planning problems, and production sequencing for scheduling problems.

Between the two concepts of "heijunka" mentioned above, "leveling of total amount" is mainly considered in production quantity planning problems involving aggregate production planning, and "leveling of quantity by item" is mainly considered in load planning problems involving master production scheduling or scheduling problems involving production sequencing. In the field of production sequencing, many studies have been conducted on leveling of quantity by item to address scheduling problems; for example, the determination of production order for each unit in an assembly line (Tamura et al. 2011, Yavuz and Akçali 2007, Just-in-time production system study group 2004, Kubiak 1993) and the determination of production order per lot in a job shop (Korytkowski et al. 2014). But in the field of aggregate production planning, the study on heijunka (leveling of total amount) has not progressed to a great extent (Tamura and Kojima 2013).

Solutions (methods) for such production planning problems often depend on the type of problem, and typical solutions exist for each problem (Kuroda 1994). Among them, linear programming methods offer a typical solution to the production quantity planning problem in aggregate production planning (Kuroda 1994, Buffa and Miller 1979). In linear programming methods, under stochastic but stationary demand (mainly for short-term irregular fluctuations of demand), the total cost, which includes the manufacturing and inventory costs, is minimized considering various elements and data, such as the time required to produce one unit of the product, regular time, overtime, backlog, materials, and the cost of each unit. Therefore, when applying these methods to practical problems, the number of elements and constraints on the relationships between elements become complicated, which may lead to an increase in calculation time (Buffa and Miller 1979). Furthermore, when the demand fluctuation is large, such as for seasonal products, the problem becomes more complicated as the number of conditions to be considered, such as the arrangement of workers and relocation, also increases.

Nevertheless, aggregate production planning is required to ensure consistency between the business plan (corporate planning/finance department), sales plan (sales department), and manufacturing resource plan (production department) as part of the company-wide "Sales and Operations Planning" (S&OP) process in a timely and effective manner (Bowersox et al. 2010). In addition, it is necessary to save calculation time in order to coordinate with the sales plan and the budget plan reflecting the latest demand trends in the S&OP process and secure time for subsequent detailed production and procurement planning. Furthermore, when coordinating among plans and departments, it is necessary to use common terms for planning quantities that are easy to understand, and terms like "sales (demand) quantity", "production quantity", and "inventory quantity" are often used to refer to planning quantities.

Therefore, by focusing on the demand, production, and inventory quantities often used in coordination among plans and departments as the basic elements of aggregate production planning, we have developed a new method for determining the production quantity that is balanced (harmonized) between inventory reduction and heijunka (production leveling) as simply as possible, based on the demand and inventory quantities. It should be noted that the main fluctuation in the demand of seasonal products is not considered to be a stationary and irregular (random) fluctuation, but a large seasonal fluctuation, and we consider it as the deterministic seasonal fluctuation.

Generally, in agile production, it is necessary to reduce costs related to inventory management by reducing the inventory quantity. In contrast, to reduce manufacturing costs, it is necessary to utilize workforce and production facilities effectively through production leveling, which minimizes fluctuations in the production quantity, thereby stabilizing it. Based on the study of Yamashita (2010), if inventory management cost is captured by its workload (energy), then cost reduction on inventory management through inventory reduction corresponds to lowering (decreasing) the inventory management energy. Furthermore, if production leveling is considered as entropy, equalization (equally distributed state) of production allocation through leveling can be regarded as increasing the entropy of production allocation (i.e., heijunka entropy). Therefore, the policy-mix problem of inventory reduction and production leveling can be treated as a balancing (harmonized) problem between lowering the inventory management energy and increasing the heijunka entropy. To formulate the aforementioned harmonized problem simply, Kurihara and Yamashita (2013) applied the “maximum entropy principle” (Jaynes 1957), which is positioned as the center of the principles described by entropy.

The maximum entropy principle (Jaynes 1957) is a general principle on “extended reasoning,” which is probabilistically evolved reasoning, such that conclusions cannot be obtained only with given evidence (Klir and Folger 1988). That is, in the maximum entropy principle, when attempting to estimate the probability distribution from insufficient evidence, it is a rational choice to select a distribution with maximum uncertainty (entropy) among all the probability distributions according to the evidence, in order to recognize adequately that the evidence is inadequate. To estimate the production quantity only with demand and inventory quantities based on the maximum entropy principle in a simple fashion, Kurihara and Yamashita (2013) considered that the maximum leveling state corresponds to the maximum uncertainty (entropy) from the viewpoint of dispersion, and formulated it as the maximization problem φ of the heijunka entropy H, maintaining the average-inventory management energy E at a constant C, as follows (the base model).

$$\varphi = H + \lambda(E - C) + \mu\left(\sum_{t=1}^{T} p_t - 1\right) \rightarrow \max. \quad (1)$$

However, λ and μ are Lagrange multipliers, and the definitions of H and E are as follows.

$$H = -\sum_{t=1}^{T} p_t \log p_t \quad (2)$$

$$E = \alpha S = \alpha \sum_{t=1}^{T} \left\{ \frac{a_{t-1} + a_t}{2} \right\} \quad (3)$$

T: the number of months included in the planning horizon
t: month index, t = 1, 2, ..., T
d_t: demand quantity at month t
p_t: production allocation rate at month t ($\sum_{t=1}^{T} p_t = 1$)
a_t: inventory quantity at the end of month t
S: the sum of average inventory quantity for T months
α: inventory management energy coefficient (inventory management energy per unit of inventory and coefficient determined by product characteristics, such as inventory management cost, risk, and influence on cash flow of holding inventory)

Accordingly, Kurihara and Yamashita (2013) derived the following solution. First, assuming that the initial inventory is set to a_0 and the ending inventory is set to a_T, the total amount of production (M) is expressed in Eq. (4), and the production quantity at month t (m_t) is expressed in Eq. (5).

$$M = \sum_{t=1}^{T} d_t - a_0 + a_T \quad (4)$$

$$m_t = p_t M \tag{5}$$

And with $x_t = \left(T - t + \frac{1}{2}\right)M$, $G = \sum_{t=1}^{T}\left\{a_0 - \left(T - t + \frac{1}{2}\right)d_t\right\}$, Q = exp [$\lambda\alpha$], Eq. (6) and Eq. (7) are obtained.

$$p_t = \frac{Q^{x_t}}{\sum_{k=1}^{T} Q^{x_k}} \tag{6}$$

$$\sum_{t=1}^{T} Q^{x_t}\left\{\alpha x_t + \alpha G - C\right\} = 0 \tag{7}$$

We numerically obtain the value of Q satisfying Eq. (7) and substitute it into Eq. (6) to obtain a solution for the production allocation rate at month t (p_t) that maximizes the entropy, and we can calculate the production quantity at month t (m_t). Consequently, we can derive the solution of the most leveled production quantity based on the demand quantity under the condition that the inventory management energy is constant with respect to the inventory level, and we can easily calculate the solution using tools such as MS Excel Solver.

There are few recent studies focused on production quantity planning problems that consider production leveling (leveling of total amount); as far as we investigated, studies by Tamura and Ohno (2013), Sato et al. (2005), and Tsubone and Tanaka (1990) can be best cited in this regard. However, the above-mentioned studies involve leveling by exponential smoothing, which consists of a method that provides approximate leveling at a fixed ratio specified by the smoothing coefficient. In addition, when finding a solution in a linear programming model, it is necessary to take into consideration various constraints related to overtime, material inventory, etc., which may increase the complexity of the model. This suggests that (1) an optimally leveled solution may not be obtained, (2) it is necessary to obtain various data describing elements and constraints, and (3) there is scope for concern regarding the adherence to deadlines and time savings required to be achieved to effectively implement aggregate production planning. In contrast, the base model can derive the most leveled solution of production quantity in a simple and timely manner based on demand quantity, because the optimal solution for leveling can be analytically obtained under a constant inventory level based on the maximum entropy principle.

A recent study that considered production stability in the same production quantity planning problem field is that of Demirel et al. (2018); it focuses on a mixed-integer linear programming model that determines the production quantity within the lower and upper bounds, called Flexibility Requirements Profile (FRP), under the indicated safety stock level against the fluctuating demand. However, this model is one that stabilizes production by suppressing fluctuations in production within a specified range; as such, it is different from the models that pursue production leveling by equalizing the production quantity such as the base model (Kurihara and Yamashita 2013) and the proposed model of this study. Furthermore, if the previous studies to be compared are expanded so as to include inventory management, a field related to aggregate production planning, the study of Kumar and Aouam (2019) on the safety stock placement problem using exponential smoothing can also be cited, as it is a recent study that takes production leveling into account. However, this study deals with the problem of determining where and how much safety stock is held for demand uncertainty (small irregular fluctuations), assuming multiple locations such as retailers and manufactures, and further uses exponential smoothing as the production leveling method. In contrast, the base model (Kurihara and Yamashita 2013) and the proposed model in this study deal with the problem of determining how much production and in which period it is needed, meeting demand with large seasonal fluctuations. Furthermore, the use of this method is based on the concept of entropy and energy as the production leveling method. Therefore, they are different in both the target problem and the method that is used.

Only a few previous studies applied the maximum entropy principle (Jaynes 1957), which is the core principle of the base model (Kurihara and Yamashita 2013), to such production quantity planning problems. Among them, we refer to the study of Tribus and Fitts (1968) and the study of Kitano et al. (1976). The difference between these previous studies and our previous study (Kurihara and Yamashita 2013) lies in the problem domain to which the maximum entropy principle is applied. That is, the problem domains of the maximum entropy principle are a decision problem on item selection for minimizing out-of-stock loss under constant production quantity in the former study (Tribus and Fitts 1968), and a decision problem on demand rate (distribution) for minimizing total cost of out-of-stock loss and inventory-keeping in the latter study (Kitano et al. 1976). In our previous study (Kurihara and Yamashita 2013), it is a decision problem on the production (allocation) rate for maximizing production leveling (heijunka) under pre-given information on demand.

In recent years, studies on applying the maximum entropy principle (Jaynes 1957) to the field of inventory management related to aggregate production planning, which deals with the "newsboy problem" (the problem of determining the appropriate purchasing and inventory quantities of short-lived products), have been conducted by Perakis and Roels (2008), Andersson et al. (2013), Maglaras and Eren (2015), and Castellano (2016), but their problem domains are also decision problems on demand distribution, which are different from the base model (Kurihara and Yamashita 2013) in both the application field and domain.

The base model can maximize the heijunka state under a constant inventory level but cannot determine the inventory state under a constant heijunka level, as exponential smoothing does. So, in this study, we extend the function of the base model and construct a harmonized model that can determine the minimized inventory state under a constant heijunka level. Like the base model, the proposed model in this study considers the harmonized problem of inventory reduction and production leveling as the harmonized problem of lowering the inventory management energy and increasing the heijunka entropy, and unlike linear programming models using exponential smoothing (Tamura and Ohno 2013, Sato et al. 2005, Tsubone and Tanaka 1990), the proposed model is a simple model with few constraints, and can minimize the inventory state based on the minimum average-energy principle.

This "minimum average-energy principle", which is a core principle of the proposed model in this study, has been studied as a basic principle in the field of thermodynamics (Fukao 1987, Callen 1985), but there are very few studies that apply the "minimum average-energy principle" in other fields. This is especially true in the field of production planning and inventory management; as far as we have examined, they cannot be found. To the best of our knowledge, the study presented here is the first research attempt to tackle the "harmonized problem between inventory reduction and heijunka (production leveling), based on the "minimum average-energy principle".

3. Research methodology/approach

3.1 Approach of this study

In this study, to build on our basic concept with respect to harmonizing between lowering the inventory management energy and increasing the heijunka entropy in production planning quantity problems, we construct a model that minimizes the inventory state (objective function) under a constant heijunka level (constraint) using a new approach. Therefore, focusing on the feature that the constraint and the objective function of the proposed model are reversed with respect to the base model, we consider it to be a dual problem in which the objective function and the constraint of the base model are exchanged, based on the studies by Fukao (1987) and Yamashita (2010).

As indicated by Fukao (1987) and Yamashita (2010), a dual problem that involves exchanging the objective function and the constraint exists against the maximization problem based on the maximum entropy principle; thus, we can consider a dual problem against the maximization problem proposed by Kurihara and Yamashita (2013), and the core principle in such a dual problem is the "minimum average-energy principle." This principle estimates the probability distribution that minimizes the average energy while maintaining the entropy at a constant magnitude. Here, assuming that "minimization of energy" indicates a tendency of concentrating and ordering inside a system, this principle is interpreted as pursuing the limit state of concentration under a certain disorder (entropy) (Fukao 1987). Therefore, in this study, the "minimum average-energy" principle is applied to pursue the limit (minimized) state for reducing the inventory quantity corresponding to the workload (energy) under a constant heijunka level (entropy). In this study, based on the minimum average-energy principle, we reconstruct the harmonized problem between inventory reduction and heijunka, and propose a new harmonized model formulated as an (average) inventory management energy minimization problem, maintaining heijunka entropy at a constant magnitude (i.e., providing a constant heijunka level) under variable demand.

As a constraint condition, it is necessary to provide a certain heijunka level using heijunka entropy. Therefore, in this study, we also use the smoothing coefficient used in exponential smoothing in fashion similar to that in linear programming models (Tamura and Ohno 2013, Sato et al. 2005, Tsubone and Tanaka 1990), and convert the heijunka level indicated by the smoothing coefficient into the heijunka entropy under a given demand.

In production planning, the exponential smoothing is often used as a simple method of smoothing (leveling) demand fluctuations, and its control indicator is a smoothing (leveling) coefficient (Korytkowski et al. 2014, Kotani 2004). For simplicity, assuming that the safety inventory, initial inventory, and ending inventory are set to 0, the relationship between d_t and m_t can be expressed as Eq. (8), if this smoothing coefficient γ is used to facilitate leveling.

$$m_t = \gamma P + (1-\gamma)d_t \tag{8}$$

However, $0 \le \gamma \le 1$

Here, the closer the smoothing coefficient γ is to 1, the more it is leveled, and the base production quantity P indicates the production quantity in the case of perfect leveling through the planning horizon, and it is expressed as Eq. (9).

$$P = \frac{M}{T} = \frac{\sum_{t=1}^{T} m_t}{T} = \frac{\sum_{t=1}^{T} d_t}{T} \tag{9}$$

Furthermore, the production allocation rate at month t (p_t) can be expressed as Eq. (10) using Eq. (5) and Eq. (8).

$$p_t = \frac{m_t}{M} = \frac{\gamma P + (1-\gamma) d_t}{M} \tag{10}$$

Therefore, the heijunka entropy H showing the leveling state corresponding to the smoothing coefficient γ can be expressed as Eq. (11) using Eq. (2) and Eq. (10).

$$H = -\sum_{t=1}^{T} p_t \log p_t = -\sum_{t=1}^{T} \left(\frac{\gamma P + (1-\gamma) d_t}{M} \right) \log \left(\frac{\gamma P + (1-\gamma) d_t}{M} \right) \tag{11}$$

Consequently, the smoothing coefficient is converted to heijunka entropy under a given demand, and it becomes possible to control the heijunka level easily through the smoothing coefficient in the proposed model. However, it should be noted that the proposed model only determines the heijunka level of the entire planning horizon; it does not determine the production quantity of each month at this point, unlike exponential smoothing, which easily and sequentially levels and determines the production quantity per month when the smoothing coefficient is specified.

Next, in order to consider prerequisites and numerical examples in the proposed model, we analyze the fluctuation in demand for seasonal products. In order to establish a comparison with the base model from the aspect of duality, domestic home air-conditioners in Japan are examined as a typical seasonal product. Then, as with the base model, we use sales data (Ministry of Economy, Trade and Industry 2011) of the air-conditioners over a span of three years (September/2007 to August/2010).

In general, the factors pertaining to demand fluctuations can be decomposed into the following four factors (Honda 2000, Makridakis and Wheelwright 1989):
(1) Trend factor: long-term change lasting in one direction
(2) Cyclical factor: wave of long-term uncertain cycles
(3) Seasonal factor: fixed cycle wave in a one-year cycle
(4) Irregular/Random factor: irregular fluctuations occurring in a short period

The trend and cyclical factors are long-term factors, and the seasonal and irregular factors are short-term factors. In aggregate production planning, the short-term factors are mainly considered because the planning horizon is generally one year (12 months) to three months.

Previous studies on linear programming models (Tamura and Ohno 2013, Sato et al. 2005, Tsubone and Tanaka 1990) focused on products with irregular fluctuation as demand fluctuation, and they considered them as a stochastic but stationary demand. However, in this study, as we focus on seasonal products with large seasonal fluctuations and construct a simplified model under such large fluctuations, we consider them to represent a deterministic demand with seasonal fluctuations of fixed cycle waves.

Table 1 and Figure 1 show the demand fluctuations of domestic home air-conditioners in Japan. Here, a seasonal fluctuation is regarded as a monthly (considered over 12 months) fluctuation occurring in the same year, an irregular fluctuation is regarded as an annual (considered over 3 years) fluctuation occurring in the same month each year, and the fluctuation state is represented by the CV (Coefficient of Variation = Standard deviation / Average) parameter. The seasonal fluctuation of home air-conditioners ranges from 0.68 to 1.01, whereas the irregular fluctuation ranges from 0.08 to 0.31, as shown in Table 1. From these values, it is possible to understand the magnitude of the seasonal fluctuation when compared to the irregular fluctuation, and they support the validity of the problem setting for the seasonal and deterministic fluctuation.

Table 1. Monthly sales data of home air-conditioners in Japan
(From Sept./2007~Aug./2010; Unit (10,000))

	Sept./2007~ Aug./2008	Sept./2008~ Aug./2009	Sept./2009~ Aug./2010	Average	Standard Deviation	CV
Sept.	29.74	21.74	13.41	21.63	6.67	0.31
Oct.	15.50	14.55	9.91	13.32	2.44	0.18
Nov.	21.57	25.10	15.64	20.77	3.91	0.19
Dec.	30.46	24.74	18.52	24.57	4.87	0.20
Jan.	19.39	19.64	14.81	17.95	2.22	0.12
Feb.	20.17	16.53	14.13	16.95	2.48	0.15
Mar.	23.57	16.63	19.12	19.77	2.87	0.15
Apr.	23.11	16.19	15.34	18.21	3.48	0.19
May	47.96	32.30	28.24	36.17	8.50	0.24
June	74.67	61.18	69.71	68.52	5.57	0.08
July	163.89	88.68	128.40	126.99	30.72	0.24
Aug.	71.01	44.41	89.53	68.31	18.52	0.27
Average	45.09	31.81	36.40			
Standard Deviation	40.59	21.61	36.68			
CV	0.90	0.68	1.01			

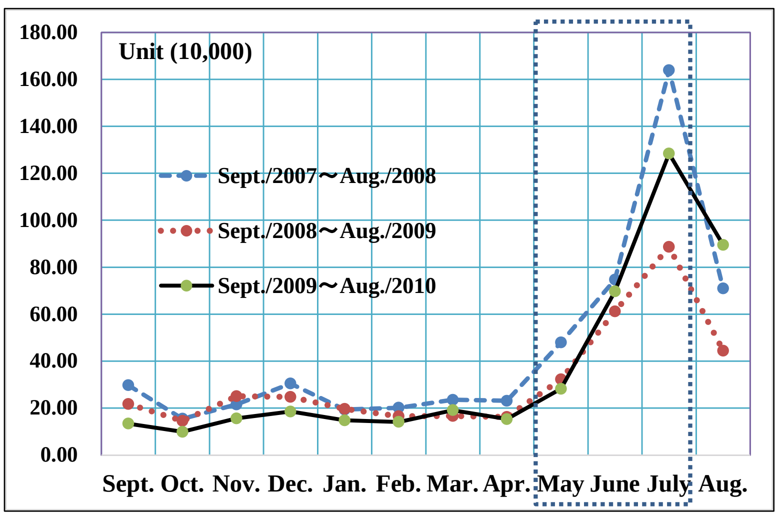


Figure 1. Demand fluctuation pattern of home air-conditioners in Japan

In addition, when the size of the seasonal fluctuation is considered as the ratio of the maximum demand (July) to the minimum demand (October), it is equal to 9.5; the demand particularly soars by 3.5 times its value from May to its peak value in July. Consequently, it is difficult to harmonize inventory reduction and heijunka in such a way that the maximum demand can be met effectively. Therefore, in the setting of the numerical example, the period from May to July is taken as the planned period to be verified, as in the case of the base model.

3.2 Prerequisites

In this study, we focus on aggregate production planning of seasonal products, and with regard to the "harmonized problem of inventory reduction and heijunka", we examine the prerequisites for constructing the simplest possible model while capturing the essence of the harmonized problem.

First, as explained in the previous section, we consider the deterministic seasonal fluctuation as the demand fluctuation, but do not consider the stationary and stochastic fluctuations such as the irregular fluctuation. Therefore, we do not consider safety inventory corresponding mainly to the stationary and stochastic fluctuation. Furthermore, in this study, we take a stand not to miss a sales opportunity, and consider that production can take place ahead of demand by leveling to cope with fluctuations in demand and planned inventory, even if the demand surges beyond the capacity and resource limits. Therefore, we do not consider the production capacity and resource restrictions that might result in the loss of sales opportunities, and do not consider the resulting out-of-stock scenario. At this time, because it is sufficient to consider "leveling of the total amount" as aggregate production planning, the number of product items may be one.

The above prerequisites are considered to be the main differences from the linear programming models dealt with in other previous studies, but they are the same as our base model (Kurihara and Yamashita 2013). However, in this study, the heijunka level is indicated with the smoothing coefficient being known, as is the case with exponential smoothing used in other previous studies, which is different from the base model in which the inventory level (inventory management energy) is known.

The main prerequisites for formulating the problem are as follows:
(1) The demand is known and deterministic.
(2) The safety inventory is not considered.
(3) There is no out-of-stock situation.
(4) The constraints on capacity and resources are not considered.
(5) The number of product items is one.
(6) The smoothing coefficient is known.

3.3 Problem formulation

The constant heijunka entropy (the heijunka level corresponding to the smoothing coefficient, which is calculated based on Eq. (11) in the previous section) is set as C. The harmonized problem φ in this study can be formulated as in Eq. (12), considering the minimization problem of the inventory management energy E under the heijunka entropy H of Eq. (2) maintained at constant C.

$$\varphi = E - \theta(H - C) - \mu\left(\sum_{t=1}^{T} p_t - 1\right) \to \min. \tag{12}$$

However, θ and μ are Lagrange multipliers.

3.4 Derivation of solutions

The solution of the harmonized problem φ in Eq. (12) is derived through the following procedure. First, from the previous study of Kurihara and Yamashita (2013), S, which is the sum of the average inventory quantity for T months, is expressed as in Eq. (13).

$$\begin{aligned} S &= \sum_{t=1}^{T}\left\{\frac{a_{t-1}+a_t}{2}\right\} = \sum_{t=1}^{T} a_t - \frac{(a_T - a_0)}{2} = \sum_{t=1}^{T} a_0 + \sum_{t=1}^{T}\sum_{k=1}^{t} m_k - \sum_{t=1}^{T}\sum_{k=1}^{t} d_k - \frac{(a_T - a_0)}{2} \\ &= \sum_{t=1}^{T}(T-t+1)m_t - \sum_{t=1}^{T}(T-t+1)d_t + \sum_{t=1}^{T} a_0 - \frac{\left(\sum_{t=1}^{T} m_t - \sum_{t=1}^{T} d_t\right)}{2} \\ &= \sum_{t=1}^{T}\left(T - t + \frac{1}{2}\right)p_t M + \sum_{t=1}^{T}\left\{a_0 - \left(T - t + \frac{1}{2}\right)d_t\right\} \end{aligned} \tag{13}$$

With $x_t = \left(T-t+\frac{1}{2}\right)M$, $G=\sum_{t=1}^{T}\left\{a_0-\left(T-t+\frac{1}{2}\right)d_t\right\}$, Eq. (3) becomes Eq. (14).

$$E=\alpha S=\alpha\sum_{t=1}^{T}p_t x_t+\alpha G \tag{14}$$

Accordingly, the harmonized problem φ of this study can be rewritten as Eq. (15).

$$\varphi=\left(\alpha\sum_{t=1}^{T}p_t x_t+\alpha G\right)-\theta\left(-\sum_{t=1}^{T}p_t\log p_t-C\right)-\mu\left(\sum_{t=1}^{T}p_t-1\right)\rightarrow \min. \tag{15}$$

As Eq. (15) is convex downward with respect to p_t, φ is partially differentiated with respect to p_t and is set to 0.

$$\frac{\partial\varphi}{\partial p_t}=\alpha x_t-\theta\left(-\log p_t-1\right)-\mu=0 \tag{16}$$

Eq. (16) is arranged regarding p_t as follows:

$$p_t=\exp\left[-1-\left(\frac{\alpha}{\theta}\right)x_t+\frac{\mu}{\theta}\right] \tag{17}$$

As Eq. (17) is obtained for each period t, dividing the respective equations by the sum of the T equations ($\sum_{k=1}^{T}p_k=1$),

$$p_t=\frac{\exp\left[-1-\left(\frac{\alpha}{\theta}\right)x_t+\frac{\mu}{\theta}\right]}{\sum_{k=1}^{T}\exp\left[-1-\left(\frac{\alpha}{\theta}\right)x_k+\frac{\mu}{\theta}\right]}=\frac{\exp\left[-\left(\frac{\alpha}{\theta}\right)x_t\right]}{\sum_{k=1}^{T}\exp\left[-\left(\frac{\alpha}{\theta}\right)x_k\right]} \tag{18}$$

With $Q=\exp\left[\frac{\alpha}{\theta}\right]$, Eq. (18) becomes Eq. (19).

$$p_t=\frac{Q^{-x_t}}{\sum_{k=1}^{T}Q^{-x_k}} \tag{19}$$

And, Eq. (20) is obtained from Eq. (15).

$$-\sum_{t=1}^{T}p_t\log p_t-C=0 \tag{20}$$

Furthermore, if Eq. (19) is substituted into Eq. (20), Eq. (21) is obtained.

$$-\sum_{t=1}^{T}\left(\frac{Q^{-x_t}}{\sum_{k=1}^{T}Q^{-x_k}}\right)\log\left(\frac{Q^{-x_t}}{\sum_{k=1}^{T}Q^{-x_k}}\right)-C=0 \tag{21}$$

Therefore, Q, which satisfies Eq. (21), is numerically obtained, and p_t (production allocation rate), which minimizes φ in Eq. (12) (inventory management energy E), is obtained by substituting Q into Eq. (19). By substituting p_t into Eq. (5), it is possible to estimate m_t (production quantity at month t).

From the above information, it can be seen that the proposed model is a simple model that has only two constraints on the heijunka level and the production allocation rate, under the deterministic demand, as shown in equation (15), and it can obtain the optimal solution (the production allocation rate) of the model analytically from Eq. (21) and Eq. (19), unlike the models of the previous studies (Tamura and Ohno 2013, Sato et al. 2005, Tsubone and Tanaka 1990). Furthermore, the solution can be easily found using low-cost, standard software, such as MS Excel Solver.

Comparing Eq. (6), which is the solution of the base model (Kurihara and Yamashita 2013), with Eq. (19), which is the solution of the model proposed herein, it is observed that the same result is obtained in the form. Fukao (1987) indicated that the dual problem based on the minimum average-energy principle, which exchanged the objective function and the constraint of the maximum entropy principle, provides the same result in the form, and this result verifies the duality of the proposed model to the base model from the theoretical aspect.

4. Analysis with simple numerical examples

4.1 Analysis method

We analyze the results of the numerical examples based on the following aims.
(1) In order to verify the validity of the proposed model from the functional aspect, we analyze it mainly on the validity of the results (inventory state) under several conditions (heijunka levels), targeting a planning horizon where harmonization of inventory reduction and heijunka (production leveling) is difficult.
(2) We also confirm that the proposed model is dual to the base model (Kurihara and Yamashita 2013) from the analysis of the numerical examples.
(3) In order to verify the effectiveness of the proposed model, we compare and analyze the results with other previous studies under the same conditions (deterministic and large seasonal fluctuations) focusing on "exponential smoothing" of aggregate production planning (Tamura and Ohno 2013, Sato et al. 2005, Tsubone and Tanaka1990), which determine inventory states by indicating the smoothing coefficients, as in this study.

We will attempt to analyze simple numerical examples based on the results of sales data pertaining to domestic home air-conditioners in Japan (Ministry of Economy, Trade and Industry "Monthly Sales Statistics Survey of Mass Retailers of Home Electric Appliances", 2011) mentioned in "3.1 Approach of this study", and based on our previous study (Kurihara and Yamashita 2013). Therefore, based on Table 1, for the three months (May–July) where the demand rises sharply toward its peak, the demand quantity d_t is considered as the three-year average (rounded to the first decimal place), as in our previous study, and a numerical example is set, as shown in Table 2. In addition, for simplicity, the initial inventory a_0 and the ending inventory a_T are set to 0, and the inventory management energy coefficient α is set to 1. Furthermore, to focus on analyzing the influence of the difference in smoothing coefficient γ on the minimum value of inventory management energy, three cases of heijunka levels, i.e., complete heijunka level (γ = 1), fair heijunka level (γ = 0.5), and intermediate level (γ = 0.8) are set, as shown in Table 3. The constant (heijunka) entropy in Table 3 is calculated based on Eq. (11), under the demand quantities in Table 2.

Table 2. Demand per month (From May to July)

Month	May	June	July	Total
	$t = 1$	$t = 2$	$t = 3$	
Demand quantity d_t	36	69	127	232
Demand rate	0.1552	0.2974	0.5474	1.0000

Table 3. Case setting

Case	Smoothing Coefficient γ	Production allocation rate *			Constant entropy C
		p_1	p_2	p_3	
Case 1	1	0.3333	0.3333	0.3333	1.09861
Case 2	0.8	0.2977	0.3262	0.3761	1.09392
Case 3	0.5	0.2443	0.3153	0.4404	1.06939

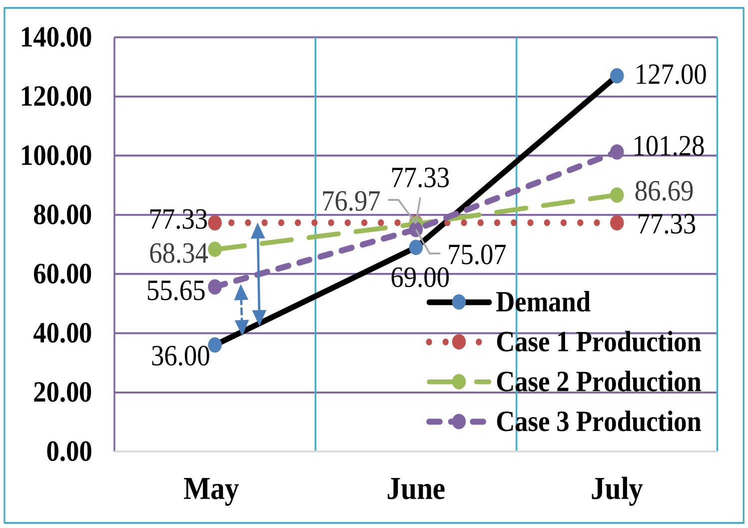
* Production leveling based on the exponential smoothing

4.2 Results

Table 4 shows the results of the minimum value of the inventory management energy for each case under numerical examples, as shown in Table 2 and Table 3. Figure 2 shows the demand quantity and determined production quantity for each case from May to July, based on the results of Table 4.

When the smoothing coefficient is small and not leveled significantly (case 3 where the entropy indicating the heijunka level is small), as shown in Figure 2, the monthly production quantity is closer to the demand quantity when compared with the other cases, and it indicates that the production agility to respond quickly to demand fluctuations (production capacity flexibility) is high; consequently, as shown in Table 4, the inventory management energy required according to the inventory state is small, but the entropy indicating the heijunka level is also small. In contrast, when the smoothing coefficient is large (case 1), the entropy indicating the heijunka level is large compared with the other cases, as shown in Table 4, but the dotted line indicating monthly production quantity in Figure 2 is apart from the solid line indicating demand quantity and it indicates that the production capacity flexibility is low; consequently, as shown in Table 4, the inventory management energy according to the inventory state also increases. These results are reasonable. Showing these results in the planning horizon—where harmonization of inventory reduction and heijunka is difficult because of a sharp increase in demand—supports the functional validity of the proposed model.

Table 4. Minimum inventory management energy *E*



Case	Constant entropy C	Production allocation rate*			Minimum inventory management energy E
		p_1	p_2	p_3	
Case 1	1.09861	0.3333	0.3333	0.3333	91.00
Case 2	1.09392	0.2946	0.3318	0.3736	72.66
Case 3	1.06939	0.2399	0.3236	0.4365	45.37

* Production leveling based on the method of the proposed model

Figure 2. Demand quantity and production quantity determined for each case

5. Discussion

Table 5 shows the result of obtaining the maximum value of the heijunka entropy for each case, assuming the inventory management energy determined in Table 4 to be constant, based on the base model (Kurihara and Yamashita 2013), which is dual to the model proposed herein. It is understood that the dual relationship between the model proposed herein and the base model (Kurihara and Yamashita 2013) exists, by comparing the relationship between the constant heijunka entropy and the minimum inventory management energy in Table 4 and the relationship between the constant inventory management energy and the maximum heijunka entropy in Table 5. Thus, we can confirm that the model proposed herein is dual to the base model (Kurihara and Yamashita 2013) from the analysis of the numerical examples.

Table 5. Maximum heijunka entropy *H*

Case	Constant inventory management energy *C*	Maximum heijunka entropy *H*
Case 1	91.00	1.09861
Case 2	72.66	1.09392
Case 3	45.37	1.06939

Furthermore, in order to analyze the difference in the inventory state to be determined between the exponential smoothing method (Tamura and Ohno 2013, Sato et al. 2005, Tsubone and Tanaka 1990) and the leveling method of the proposed model, we compare the production allocation rate determined by the exponential smoothing given in Table 3 with the production allocation rate determined by the proposed model in Table 4. In case 1, which is completely leveled, both provide equal rates and the same result is obtained. But in case 2 and case 3, which are not completely leveled, the production allocation rates in Table 3 and Table 4 are slightly different. This is because the exponential smoothing (Tamura and Ohno 2013, Sato et al. 2005, Tsubone and Tanaka 1990) easily and sequentially levels demand based on the smoothing coefficient and determines a monthly production allocation rate that is approximately leveled (typically resulting in a higher inventory state) (Table 3). In contrast, the proposed model considers the smoothing coefficient as the heijunka level over the whole planning horizon, and determines the monthly production allocation rate that minimizes the inventory management energy (inventory state) under the heijunka entropy (constant entropy) corresponding to the smoothing coefficient in Table 3, based on the minimum average-energy principle (Table 4).

Table 6 summarizes the results by adding case 4 (γ = 0.2) to the case settings in Table 3 (γ = 1.0, 0.8, 0.5), in order to compare the change in the difference of inventory state (inventory management energy) between the exponential smoothing and the proposed model due to the difference of the smoothing coefficient. For the reasons explained above, Table 6 shows that the inventory status determined by the proposed model is 0.09% to 0.28% lower than the exponential smoothing model of aggregate production planning (Tamura and Ohno 2013, Sato et al. 2005, Tsubone and Tanaka 1990) in all cases except for case 1. The difference between the model of exponential smoothing and the proposed model is less than 1%, confirming that exponential smoothing is valid as an approximate leveling method. At the same time, we can also notice that the difference between the solution of exponential smoothing and the optimal solution of the proposed model is small (0–0.19%) in the case of production with an emphasis on heijunka (large smoothing coefficient: 1.0, 0.8) or production with an emphasis on inventory reduction (small smoothing coefficient: 0.2); however, this difference becomes large (0.28%) in the case of production that emphasizes balancing (harmonizing) inventory reduction and heijunka (fair smoothing coefficient: 0.5). In such a situation, expensive products that must have a large inventory because of the large volume fluctuations in demand, such as home air-conditioners (Table 1), may have a considerable impact on corporate management from the standpoint of inventory-related costs. Therefore, if the proposed model of this study is applied to the aggregate production planning of these products that seeks harmonization between inventory reduction and heijunka, it is possible to achieve an optimal inventory state lower than the state of exponential smoothing and further reduce the inventory-related cost, even if the same smoothing coefficient is used as a condition of the production leveling.

Table 6. Leveling method and inventory management energy

Case	Exponential smoothing		Proposed model		Difference	Difference rate
	Smoothing coefficient γ	Inventory management energy *e*	Heijunka entropy *H*	Inventory management energy *E*	$\Delta e = E - e$	$\Delta e/e$
Case 1	1	91.00	1.09861	91.00	0.00	0.00%
Case 2	0.8	72.80	1.09392	72.66	-0.14	-0.19%
Case 3	0.5	45.50	1.06939	45.37	-0.13	-0.28%
Case 4	0.2	18.20	1.02331	18.18	-0.02	-0.09%

The above results suggest that the proposed model is a simple model based on the minimum average-energy principle, focused on the relationships among demand, inventory, and production, but it can find the optimal solution that minimizes the inventory state even under rapidly changing demand scenarios by indicating the heijunka level through the smoothing coefficient. The proposed model complements the base model, which maximizes the heijunka state under an indicated inventory level, and it can also be applied to planning and adjustment of aggregate production planning, especially production-sales-inventory planning, in a timely and effective manner by manufacturers of seasonal products, taking advantage of its simplicity.

6. Conclusion

In this study, we propose a dual approach to the base model we previously developed in order to construct a new harmonized model of inventory reduction and production leveling ("heijunka") in aggregate production planning, and propose our harmonized model that minimizes inventory status (inventory management workload/energy) based on the minimum average-energy principle, under a given level of heijunka (smoothing coefficient/heijunka entropy). Based on the results of an analysis involving simple numerical examples, we verify that the approach and model proposed in this study are valid, and the solution (inventory status) of the proposed model is both optimized and better than the solution of exponential smoothing under the same heijunka level. In addition, we find that the difference between solutions is the largest in the case of a medium smoothing coefficient (i.e., production with an emphasis on harmonization between inventory reduction and heijunka). In contrast to the exponential smoothing method (Tamura and Ohno 2013, Sato et al. 2005, Tsubone and Tanaka 1990), which approximates leveling by sequential smoothing, and the FRP method (Demirel et al. 2018), which stabilizes production by keeping fluctuations within a specified range, the method of this study to pursue optimal leveling throughout the planning horizon enables us to seek the optimal production quantity that minimizes the inventory management energy (workload) associated with the inventory quantity, under the current production facilities and capabilities (i.e., the given level of heijunka). Moreover, by adding the minimization of inventory management energy to maximization of heijunka entropy, multifaceted analysis on the harmonized level between inventory reduction and heijunka will be possible in aggregate production planning. The aforementioned studies are the theoretical contributions of this study.

In the proposed model, by focusing on demand quantity, inventory quantity, and production quantity, and by applying the minimum average-energy principle, the essence of the harmonized problem of inventory reduction and heijunka is captured and formulated in a simple fashion, and the optimal solution of the formulated problem can be obtained. By applying this model to the manufacturing of seasonal products with large demand fluctuations as discussed in Section 5, timely aggregate production planning (especially production-sales-inventory planning) and the adjustment among plans and departments (planning and finance departments, sales department, manufacturing department) can be made easier. In addition, it is possible to apply it to aggregate production planning in SMEs because it is easy to obtain the necessary input data because of the few types of data used, and it can find the optimal solution using low-cost, standard software, such as MS Excel Solver. The aforementioned aspects are the practical contributions of this study.

However, the limitations of this study lie in its set of prerequisites. In order to construct a simple model, prerequisites based on the characteristics of the demand for seasonal products are set along with the application of: (1) the concepts of entropy and energy, and (2) application of the minimum average-energy principle. Therefore, if applied to more detailed aggregate production planning of seasonal products or aggregate production planning of products mainly for stochastic and stationary demand fluctuation, it is necessary to review the prerequisites such as the number of items, fixed demand (including safety inventory, out of stock), and capacity constraints and relax them. These are the limitations of the "harmonized model between inventory reduction and heijunka" including the proposed model of this study.

In the future, to expand the applicability in practice while taking advantage of the characteristics of a simple model based on the concepts of entropy and energy, focusing especially on prerequisites (5), we would like to attempt the development of a harmonized model between inventory reduction and heijunka that addresses the limitation of this study and expands the target from a single item to multiple items.

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