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Impact of dynamic capacity policies on WIP level in mix leveling lean environment

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Abstract

Balancing demand's product variety in production planning is one aspect of variety management challenge. This phenomenon is described in lean systems as mix leveling. This paper approach product mix leveling problem from a dynamic perspective. A system dynamics model is developed to explore the dynamics associated with the WIP level performance at different mix leveling policies in a lean environment. The system captures different lean tools and policies. Results showed that the best WIP performance is sensitive to both the degree of lean tools implementation as well as the capacity scalability level of the system. The presented analysis showed that dynamic capacity is essential for successful mix leveling policies; however, investments in such scalability can be minimized with shorter production cycles as well as efficient JIT implementation. In addition, the positive impact of SMED on WIP accumulation in lean environment was well demonstrated.

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Keywords: *Mix leveling, lean dynamics, WIP*

1. Introduction

Efficient production leveling in terms of volume and mix to eliminate over-production (as one form of wastes), is among the fundamental targets of lean manufacturing. Over-production means producing more, sooner or faster than is required by the next process [1]. Over-production causes additional handling, inspecting, counting and storing costs of those not yet needed products. In addition, with over-production, WIP levels increases and defects remain hidden in the WIP until the downstream process finally uses the parts and quality issues are discovered. Heijunka is the Japanese term for load or production leveling which is the lean manufacturing strategy employed to eliminate over-production. Leveled production attains capacity balance and synchronization of all production operations over time in a manner that precisely and flexibly matches customer demand for the system's products. Ideally, this means producing every product in every shift in quantities equal to demand after smoothing out high frequency random components. Manufacturing processes should be operated at the takt time to achieve level production.

This paper investigates the impacts of one of the two aspects of production leveling which is mix leveling over one of the fundamental wastes encountered by over production which is the accumulated WIP level. Dynamic analysis of various mix leveling policies in a lean cell employing dynamic capacity and producing at takt time will be tested against accumulated WIP levels. The overall objective of the analysis is to gain better understanding of how to set mix leveling policies in similar lean environment while managing the capacity scalability effort, lean implementation costs and accumulated WIP levels.

2. Literature review

Extensive review about lean manufacturing definitions, their development and related research work can be found in [2-4]. In this section, particularly focus is placed on related body of work which explores lean implementation's dynamic

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modeling and analysis with more emphasis on implementation of production leveling approaches. Various research works focused on the general implementation of lean systems from dynamic perspective. The dynamics of process design in lean systems implementation using a dynamic value stream mapping approach was investigated by Kodua et al. [5]. They focused on how to change organizations decisions in accordance to product realization requirements using a dynamic modeling approach. A group of qualitative and quantitative dynamic rules to implement lean manufacturing were presented [6]. The approach focused on how to make current mass production industrial operation leaner. Axiomatic design principles were applied to design lean manufacturing systems with focus on line segmentation [7]. They showed that integrating axiomatic design with lean management improved the design and performance of manufacturing systems. The use of discrete event simulation (DES) as a tool to assist organizations with the decision to implement lean manufacturing by quantifying the operational benefits achieved from applying lean principles was demonstrated [8]. Other simulation studies were also conducted to investigate the impact of Just in Time (JIT) and pull lean principles on improving manufacturing system operational performance [9 and 10]. The approach by lian et al. [11] combined simulation and value stream mapping together with existing data bases of production to develop a tool for assessing lean implementation. They introduced a model generator to compare the current and the future system, based on improving the value stream. The comparison allows mangers to make better decisions on when, where and how to implement lean manufacturing from a value perspective. DES was also used to examine impact of implementing both Lean and Green policies on overall system performance [12]. They presented a case study which showed that when Lean and Green techniques are well tailored to the system using simulation, optimal system performance can result.
Specific implementation of production leveling (Heijunka) includes the early work of Monden [13] who suggested a simple algorithm for Heijunka scheduling that has been used in practice. It was noted that implementation of Heijunka was only possible when few schedule disturbances existed i.e. demand was relatively stable and predictable [14]. The trade-off between Heijunka and system's responsiveness was also demonstrated [15]. An automotive case study was used to demonstrate the need to balance between Heijunka and the Just in Sequence approach if the customer requirements are dynamic in nature [16]. A dynamic capacity scalability mechanism that incorporates the accumulated backlog and WIP levels to better manages the trade-off between Heijunka and responsiveness was also suggested [17 and 18].

The previous work focused on successful implementation of various lean techniques while few only focused on production leveling. The analysis of production leveling dynamics was directed to explore the impact of such principle on responsiveness while less attention was paid to the impact of this lean principle on accumulated WIP over time. This paper shed some light on the dynamics associated with production leveling in lean environment with focus on WIP as key performance indicator.

3. Dynamic Lean Cell

The system dynamic model for a lean manufacturing cell by [17] is adopted and modified to incorporate production leveling lean mechanisms. The new model is shown in figure 1. The displayed system is composed of a demand component that captures the stochastic nature of the demand and translates it to takt time and pull rate. The production component is modeled as a lean cell with three production centers or stations. The production is controlled by a pull rate which is function of takt time and is affected by the availability of materials via the JIT mechanism. The production leveling is maintained through a sequencing policy which impacts the change-over time and also through a scalable capacity component. The backlog of the developed cell is monitored as well as the accumulated overall WIP level. Each of these system's components and their interactions are discussed in details in this section

Nomenclature

B(t)	the backlog level at time t.
WIPi(t)	the WIP level at time t at station i.
IPR(t)	the input production rate.
PR(t)	the pull rate.
PSR(t)	the production start rate at time t.
AD(t)	the average demand at time t.
SD	the standard deviation for demand distribution
Avab.	the system availability.
IO(t)	the incoming orders at time t
OO(t)	the outgoing orders at time t. It is the rate of physical product leaving the cell.
TWIP(t)	the total WIP of the system at time t.
HFO(t)	the hourly filled orders at time t.
AT	the manufacturing available time
TT	the takt time
%RC(t)	the percentage of the required capacity to be scaled at time t.
SDT	the scalability delay time
SST	the standard shift time
CO	change-over time.
COstd	standard time for each change-over
MLS	mix levelling sequence
JIT_{eff}	JIT implementation efficiency
$SMED_{eff}$	SMED implementation efficiency

3.1. Stochastic Market Demand:

The market demand is modelled as a stochastic parameter with dependent distribution or pink noise in Equations 1-2.

$$\textit{White}\text{ Noise(t)} = \text{AD(t)} + \left[SD^{2} * \frac{(2-(DT/CT))}{(DT/CT)} \right]^{0.5} * Normal(0,1,Seed) \quad (1)$$

$$\textit{Change}\text{ in Pink Noise} = \frac{\text{Pink Noise(t)} - \text{White Noise(t)}}{\text{CT}} \quad (2)$$

The demand rate (DR) is calculated in equation 3:

DR(t) = Change in Pink Noise/Unit time (3)

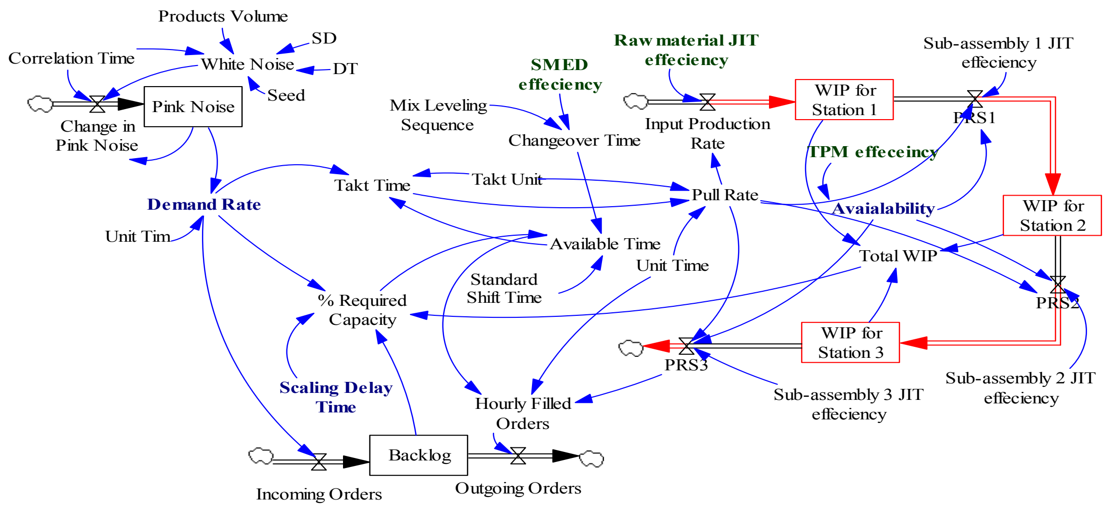


Fig. 1. Dynamics of WIP level in scalable lean manufacturing cell

3.2. Takt Time and Available Time:

Takt time is calculated by dividing available time by the customer daily demand rate as shown in equation 4:

$$TT = \frac{AT}{DR(t)} \quad (4)$$

The lean cell is augmented with dynamic capacity mechanism. Thus, the available time is calculated as function of the standard shift time (SST) plus hours based on scaled capacity if needed. The extra available time is introduced to maintain production- volume levelling. The mix policy is reflected in the model through changeover time (CO). The changeover time is calculated based on the number of changeovers multiplied by the changeover standard time in equation 5. The changeover time can be improved by efficient SMED lean mechanism. The CO is subtracted from the available time which is thus calculated (equation 6):

$$CO = (ProductionLevelingPolicy * CO_{std}) * SMED_{eff} \quad (5)$$

$$AT = SST\,(1 + \%RC) - CO \quad (6)$$

3.3. Dynamic Capacity Modeling:

The use of dynamic capacity techniques is more common within today's new paradigms of changeable and reconfigurable systems [19]. A hybrid scaling policy is employed to calculate the required scalability level based on a relative percentage of both accumulated WIP and backlog levels with respect to demand as explained by Deif [17]. The required capacity based on the hybrid policy is shown in equation 7. Scaling delay time (SDT) is also captured as instantaneous capacity scalability is impractical.

$$\%RC(t) = \left[\frac{TWIP(t) + Backlog(t)}{SDT}\right] / DR \quad (7)$$

3.4. Production Control:

The WIP level at each station in the lean cell is determined by the difference between the production rate of the current station and the production rate of the next one (equation 8).

$$\dot{WIP}_i(t) = PRS_i(t) - PRS_{i+1}(t) \quad (8)$$

To demonstrate the pull dynamics, production rate is set to be equal to a pull rate calculated based on takt time. In addition, the pull rate at each stage is also determined based on machine availability as well as readiness of materials and sub-assemblies required for each stage. To illustrate the role of lean tools in successful production levelling policies, the availability of machines can be increased by applying total productive maintenance (TPM) which is referred to as TPM efficiency. Furthermore, the readiness of materials and sub-assemblies can increase through applying JIT techniques which are referred to as JIT efficiency. The availability of each stage is stochastically modelled as random uniform distribution. The previous production dynamics are shown in equations 9-11.

$$PR(t) = (TT/Unit\ Time) * Takt\ Unit \quad (9)$$

$$IPR(t) = PR(t) * JIT_{eff_i} \quad (10)$$

$$PRS_i(t) = PR(t) * JIT_{eff_i} * Avab_i * TPM_{eff} \quad (11)$$

3.5. Backlog Calculation:

Backlog is calculated as the difference between input order rate and outgoing order rate. The outgoing order rate is a function in hourly filled order based on both production and available time. Backlog calculations are in equations 12-15

$$\dot{B}(t) = OO(t) - IO(t) \quad (12)$$

$$IO(t) = DR(t) \quad (13)$$

$$OO(t) = HFO(t) \quad (14)$$

$$HFO(t) = PRS3(t) * AT \quad (15)$$

4. Studying lean mix leveling and WIP level dynamics

A case study for a lean cell assembling consumer electronics products is adopted [8] to demonstrate the impact of mix leveling policies with dynamic capacity on accumulated WIP. The facility is composed of six identical lean cells with only four planned for production and the other two represent capacity scalability options. For analysis purposes; the production dynamics of the identical cells are aggregated into one representative cell. Two products are considered. The production process in each cell is carried out in three stations. Station one is dedicated for assembly, station two is responsible for both inspection and testing and station three is used for packing. Each station is supplied with parts from two parts storage areas and two satellite subassembly areas. Shipments are scheduled every two weeks. All analyses are monitored over a one month (160 hours). Data for the system's base case scenario is listed in table 1.

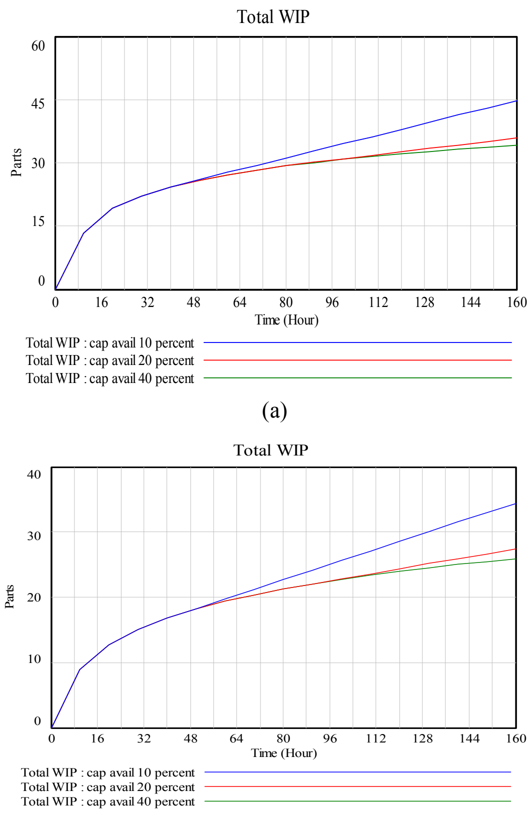
Table 1 Input data for electronic products' lean assembly cell

Parameter	Value
Demand rate (mean and standard deviation)	60 parts/hour, 12 parts/hour (20%)
Number of parts	2 parts (30 parts/hour each)
Standard shift time	8 hours/day, 40 h/week, 160 h/month
Station 1 availability	95%
Station 2 availability	93%
Station 3 availability	91%
Scaling delay time	1 hour
Change over time	0.2 hour

4.1. Impact of dynamic capacity limits on WIP level for different mix leveling policies

The impact of different capacity scalability limits for low and high product mix leveling policies on the accumulated WIP level is investigated. The purpose is to gain an initial insight into the behavior of an important internal system aspect which is the accumalted WIP level while considering the two production leveling approaches; volume leveling through capacity scalability and mix leveling through different delivery sequencing scenarios. Figure 2 displays the accumulated WIP at different capacity scaling levels (expressed as percentage of the normal available capacity) for two mix leveling scenarios. The first is for a delivery sequence of batches of size 300 of each product which will include 16 changeovers per month - this scenario is referred to as high mix leveling policy. The second scenario is for a batch size of 1200 which requires 4 changeovers per month and is referred to as low mix leveling policy. Investigating figure 2 reveals the following

- The WIP accumulation levels in both scenarios show similar behavior at different capacity scalability levels for a certain production period (around 30% of the considered period) before they become differentiated. This highlights the importance of caution with regard to deciding how much to invest in capacity scaling options relative to the planned production period (and thus the batch size). With smaller production periods, for the given settings, lower capacity scalability options will perform exactly the same as higher scaling options considering WIP level as a performance index.
- As expected, the accumulated WIP level at high mix leveling policy is higher than that at the low mix leveling. Aligning the system with high degrees of market variation (reflected in mix leveling) always has its negative impact on the system internal stability which requires a well-planned tradeoff between responsiveness level and internal production stability.
- Capacity scalability has a positive impact in managing volume leveling as well as reducing the accumulated WIP level. This is shown with the decrease of the WIP level as the scaling percentage increases. It is important to note that this is also due to the capacity scalability policy adopted in this model which takes into account the required volume leveling objective as well as accumulated WIP and backlog as explained in equation (8)



(b)

Fig. 2: WIP level performance comparison for different capacity scalability levels at (a) high mix levelling policy (b) low mix levelling policy

4.2. Impact of lean tools on WIP level at high mix leveling policies with dynamic capacity:

In this section the impact of SMED and JIT lean mechanisms on the accumulated WIP is explored. Single minute exchange of die (SMED) is a lean approach to reduce setup time to be within single digit of minutes. This mechanism is fundamental for product mix leveling since the latter requires multiple changeovers between different products during production to achieve the required market leveling. The efficiency of SMED application affects the dynamics of the modeled lean cell by decreasing the change overtime which is function in the number of mix leveling sequencing .(equation 5). Figure 3 shows the general positive impact of SMED application on the accumulated WIP at the high mix policy mentioned earlier. Also, the WIP level decreases as the efficiency of the SMED application increases highlighting the inverse proportional relationship between SMED mechanisms and WIP level at mix leveling production environment. In this analysis; high SMED efficiency decreases the C/O time by 30%, average efficiency by 20% and low efficiency by 10%.

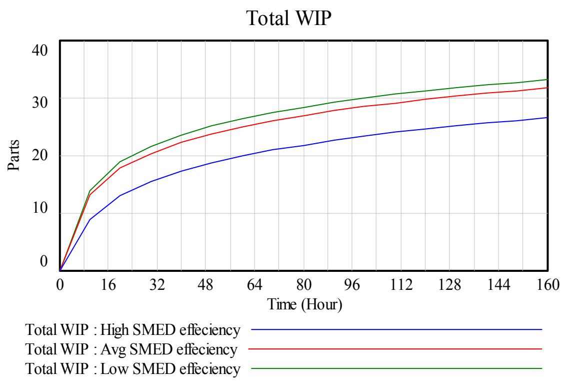


Fig. 3: WIP level performance comparison for different SMED implementation efficiency

Figure 4 demonstrates the impact of JIT mechanisms (Kanban cards, supermarkets…etc.) on the accumulated WIP. Successful JIT implementation enhances the pull rate at different stages to operate effectively at takt time. The figure compares the accumulated WIP levels at various capacity scalability limits when implementing JIT with 90% and 100% efficiency (JIT_{eff} in equation 11 equals 0.9 and 1 respectively). Analysis of these results suggests the following:

- Improving JIT implementation from 90% to 100% decreased the accumulated WIP by an average of 40%. This reduction of WIP level would help to pay for the required investment and effort to maintain JIT policies in similar lean systems.
- At high JIT efficiency, the capacity scalability limits do not affect the WIP performance. The reason behind this non-conventional finding is that at the selected setting the availability of materials with balanced pull rate at takt will help the production stages to maintain minimal WIP as long as the machine availability is high (as in the considered case). Extra capacity in such scenario would only be required when machine availability decreases. The decision to invest in capacity scalability provisions or high efficiency JIT mechanisms is left to the lean planners as it varies from one system to the other.

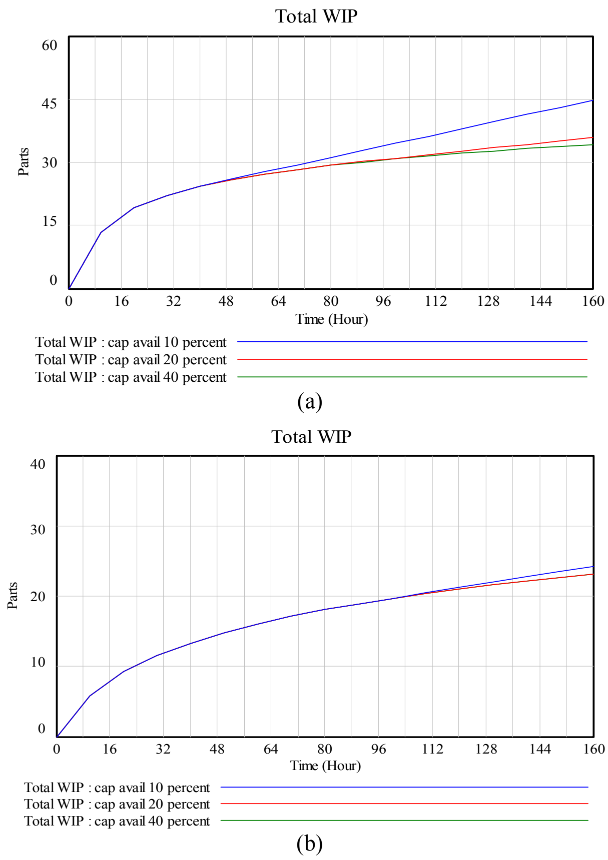


Fig. 4: WIP level performance comparison for different capacity scalability levels at (a) 90% JIT implementation efficiency and (b) 100% JIT implementation efficiency

5. Conclusions

A dynamic model for a lean cell implementing scalable capacity and capturing different lean mechanisms was developed. The analysis of the developed model focused on the impact of the scalable capacity limitations as well as successful implementation of the modeled lean mechanisms on the accumulated WIP level as a performance metric. The main findings are summarized as:

- Dynamic capacity scalability is essential for successful mix leveling policy to account for market uncertainty, changeover time and other internal disturbances. The trade-off between required cost of capacity scalability and the gained benefits in terms of market responsiveness as well as reduced WIP levels was demonstrated.
- An important practical finding concerning investing in capacity scalability options, such as additional machines, was demonstrated through the dynamics of WIP accumulation (within the selected lean settings). Results showed that minimum capacity scalability investments can pay off for cases of short production periods (i.e. small batch sizes) as well as high efficiency of JIT implementation with high machine availability.

- In mix leveling lean environment much effort needs to be dedicated to implementing single minute exchange of dies (SMED) mechanisms. The significant decrease in changeover time resulted by SMED mechanisms contributes to WIP level reduction. Such reduction should be considered for the justification of allocating resources to implement SMED.

Future research will focus on the impact of availability of machines and its lean TPM mechanism efficiency on WIP accumulation. In addition, the impact of capacity scalability delay time WIP accumulation will be explored. Finally, the effect of market uncertainty on the general lean implementation efficiency will be further investigated.

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