A pull management model for a production cell under variable demand conditions

M. Gallo, R. Revetria, and E. Romano

***Abstract*—** The objective of this work is to contribute to the understanding of the dynamics enacted by the demand variability and influencing decision-makers with their manufacturing strategies. In particular, we consider a single kanban cell, in which the main actors are typically a production department that acts as a supplier and an assembly department which acts as a customer.

This cell is subjected to a variable demand modeled as a random variable with a known statistical distribution. This variability complicates the cell operation. In order to maintain the system productivity and to limit the queues in the system, a management model for cell operation, called ”*virtual kanban strategy*", has been proposed.

In this work the authors have utilized an approach based on the system dynamics simulation model.

***Keywords*—** Computer simulation, demand variability, kanban technique, system dynamics.

I. Introduction

TODAY'S business market scenario requires new forms of competition: markets suffer from uncertainty and market demand is subject to strong turbulence, making difficult or unreliable forecasts with customers increasingly demanding.

The basic goal for companies becomes generate added value for their customers, providing what they want, when they wish, with the characteristics and conditions agreed, and associating the product a distinctive service (after sales, maintenance, warranty replacement, training in the use or whatever). To achieve this, companies must aim to operate on-demand, in order to ensure flexibility, but being effective at the same time consolidating its internal know-how and core competencies that set it apart from the competition.

In this context, lean production appears as a production model that can effectively support a production strategy pulled from the market, making it possible to adapt to customer demand and, at the same time, reduce operations. Typical results that can be achieved is reducing production costs, reducing the throughput time, increasing the inventory turns index and improving the utilization of the production capacity.

One of the techniques proposed by the TPS to synchronize production processes with customer request is the kanban system. The kanban system, however, arises as a flow control system able of supporting a variability rate relatively low and this results in a very strong limit on the possibility to implement the system in a more dynamic context.

Moreover, in this context, companies need a method of analysis to investigate business problems, and in this way a good approach is found to be the one based on System Dynamics. This provides a paradigm of analysis of companies' policies and allows for the understanding of the interactions between customers, competitors and suppliers, using feedback mechanisms.

In order to examine the factors involved in production systems variability, and, in particular, to verify the applicability of the Kanban system also outside of stable contexts, an analysis of the dynamic behavior of a system kanban is proposed.

In a unstable environment the need to make decisions taking into account the feedback information is of paramount importance. Looking at the kanban control system in a system dynamics perspective allows to analyze a priori the dynamics affecting the system due to the demand variability, will also allow decision makers to learn more about the system and to take account some unexpected effects that their actions could cause in a kanban production system.

The objective of this work is to contribute to the understanding of the dynamics enacted by the demand variability and influencing decision-makers with their manufacturing strategies. In particular, we consider a single kanban cell, in which the main actors are typically a production department that acts as a supplier and an assembly department which acts as a customer.

This cell is subjected to a variable demand modeled as a random variable with a known statistical distribution. This variability complicates the cell operation. In order to maintain the system productivity and to limit the queues in the system, a management model for cell operation, called ”*virtual kanban strategy*", has been proposed.

This strategy is based on the consideration that varying the number of cards in the system, like the Flexible Kanban System [2], improve the system performance. Basically, the

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virtual kanban strategy consists in introducing a new type of kanban labels, *the virtual kanban labels*, with the fundamental task to recover the lack of production orders on kanban box, although they are not directly linked to physical quantities.

The study of the production system is being addressed with the system dynamics approach using the simulation software Powersim Studio 5.

In particular, three simulation models has been developed:

• The first model represents the kanban cell subject to a steady demand, this is an ideal case and is intrinsically desirable to the philosophy of Lean Production;

• The second model is characterized by the variability of demand, which makes the system instable and less efficient;

• The final model adopts a Virtual Kanban Strategy in order to absorb fluctuations in demand by improving the efficiency of the system.

This paper is further organized as follows. In Section 2 the relevant literature on kanban systems with a variable number of kanban and system dynamics modeling of kanban systems is reviewed. In Section 3 the demand variability on the production processes are discussed. In Section 4 and 5, simulation model assumptions and results are presented. In section 6 simulation model based on system dynamics, with different politics, are presented. Section 7 reports the simulation model with new assumptions based on virtual kanban definition. In this section the comparison among performances output by different models are analyzed. The paper is concluded in Section 8.

II. Literature Review

The literature on kanban systems consists of thousands of articles, which describe in different ways various models of kanban systems and their control systems.

In addition there are various methods of classification for kanban systems [18], [24]. The classification used in this case is not based on structural characteristics of the kanban system, such as the number of workstations or the type of labels put in circulation, but it is focused on how the change in the number of labels in the Kanban System is managed.

In general terms, literature on Kanban systems can be split in:

• *Systems with fixed number of kanban labels;*

• *Systems with variable number of kanban labels.*

In this study we consider only those papers considering kanban systems with a variable Kanban number.

Rees et al. (1987) propose a technique for dynamically adjusting the number of Kanban; their research is an effort to study the applicability of kanban in non ideal operating conditions, such as the absence of a universally shared philosophy of JIT. The aim of the methodology is to obtain a cumulative probability distribution for the number of kanban, so to associate an occurrence probability to the number of Kanban, as a combination of demand forecasts and sampling on the production lead time. There will be shorter transient periods associated with variation in the number of Kanban [12]. Gupta et al. (1997) introduce an algorithm to systematically change the number of Kanban and offset, therefore, changes in the process time and in the demand. They use the simulation language SIMAN and they assume normally and independent distributed time for each work center and a demand for finished products evenly distributed. The new system thus implemented is called Flexible Kanban System, in which the increase in the Kanban number stimulates the production, "pulling" the system [2]. Only later, Gupta (1999) studies the performance of the FKB compared to Traditional Kanban System. He considers a stochastic JIT environment in order to introduce a systematic methodology to adjust the number of Kanban to compensate for the sources of variability.

For each of these cases the author considers a different simulation model in a SIMAN environment consisting of various modules to measure system performance [3]. The flexible system is the first example of what Takahashi and Nakamura (1999) define Reacting JIT ordering systems, which means a system based on two JIT ordering systems: the kanban system and the concurrent ordering system. This type of system is able to react to changes in demand. The aim of this model is primarily the identification of variability and the implementation of any control measure of this variability, which in this case is found in the size of the buffer. These authors study the production process using control charts around the mean of the random variable demand and they identify the deviation of the data to the process parameters. The supervisor can make a dimensioning of buffer capacity, in order to absorb fluctuations in demand, production and lead times [14]. Later, Takahashi and Nakamura (2002) and Takahashi et al. (2004) proposed respectively a decentralized reactive Kanban and an advanced reactive JIT ordering system.

In the first case the authors study the variability of demand around the mean always using the control limits obtained by EWMA control charts, and they then consequently size the buffer capacity; then the multi-stage production system is decomposed into single stage kanban systems controlled by kanban and their performance are analyzed under the same assumptions of demand variability [13].

In the second case the authors examine the characteristics of demand variability around both its parameters: mean and standard deviation, again using the method of EWMA control charts [15].

Another important area of research relevant for the present work is the modeling of kanban systems through the System Dynamics.

O'Callaghan (1986) uses the principles of System Dynamics to develop a simulation model of a kanban multi-stage system. In particular, the author analyses the response of the production system to small shocks, such as small demand variation. [20].

Gupta Y.P. and Gupta M (1989) models the behavior of a system composed of multiple production lines and a single final assembly considering a single work cell, assuming the inputs and the demand as exogenous variables. The objective of the dynamic simulation is to determine the relationship between the number of kanbans and the capacity of the kanban itself, and manufacturing efficiency, under various hypotheses of system operation [21].

Marquez et al. (1996) study the behavior of a Kanban system, comparing it with that of a CONWIP system through an approach based on casual diagrams. The CONWIP systems are shown to be more reactive to large variations in demand and consequently to large fluctuations in inventory levels; in addition, production lead time appear to be shorter than in Kanban Systems [19]. Lai et al. (2003) present a simulation model of Electronic Commerce (EC) using iThink The model consists of a platform, a Web Server, on which the exchanges between the actors involved in the process occur [22]. Tim Haslett (2003), starting from the theory that production systems become more efficient on the "edge of chaos", replicates through simulation the implementation of the Kanban technique in an automated manufacturing system. From the simulations the author argues that the system performance improvement and an increase in its instability are linked together. Moreover, the increase of instability of the system is a necessary condition for the improvement of its performance [23]. Romano E. et al. (2008 - 2010) [25, 26, 27] used different simulation languages to simulate, verify and design kanban systems in a different real production case study.

III. Analysis of Variability

In the present work the experimental observations to analyze and then model the system are not available. Usually companies have only the trend of the variables considered here and the information coming from experience.

If no experimental data are available, it is necessary to proceed through the simulation methodology. In this case, we have chosen as simulation tool the Monte Carlo method. This method allows to obtain a distribution of pseudo-experimental data for each variable on which basing all the simulation runs.

For each random variable, we generate sequences of pseudo-experimental determinations and from these we obtain the experimental data sequence. The random variables identified, x_d, w_p and ZCS, are modeled, respectively, by the following statistical distributions: normal and Beta type, with known parameters. The number of kanbans depends on these random variables representing respectively: demand, production rate and set-up time. To analyze these dependencies we have determined how the number of kanban varies in relation to each of these variables considered individually.

Consider the kanban label number formula:

$$N_{\max}^{k} = \operatorname{int}\left[\frac{x_d \cdot \left(T_r + T_a + z_{cs} + \dfrac{q}{w_p} + T_t\right) + Q}{q}\right] + 1 \quad (1)$$

Demand variability reproduces the effect on production systems caused by changes in market. These fluctuations will greatly impact the number of kanban labels in the system, this can be confirmed by a analytical procedure carried out starting from the formula *x*. In fact, considering the only variation in demand, the direct dependence existing between demand and the number of kanban can be verified.

$$N_{\max}^{k} = \operatorname{int}\left[E \cdot x_d + F\right] + 1 \quad (2)$$

It must be noted that the use of this formula implies a demand distributed as a normal variable, characterized by a certain mean and by a respective variance. The fluctuations in demand affect the value of the variance of the probability distribution. The influence that the change in demand has on the calculation of the number of labels increases as the variance of the distribution. Whereas different values of the variance, indicated with *d*, are obtained several graphs in a range that goes from 1 to 45: in which a very low variance corresponds to a demand curve very closely, which therefore constitutes an almost constant input to the system, while a high variance demand represents a critical issue for the company (Fig.1, 2 and 3). From these graphs it is possible to conclude that demand variation tends to have a strong influence on the calculation of the number of labels and so on the dimensions of the entire production system.

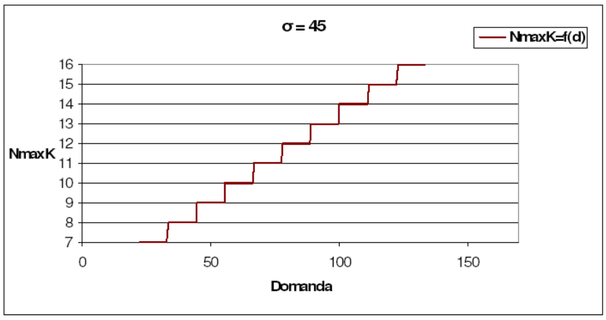

Fig. 1: Number of Kanban variation based on the defined value of demand variance (45).

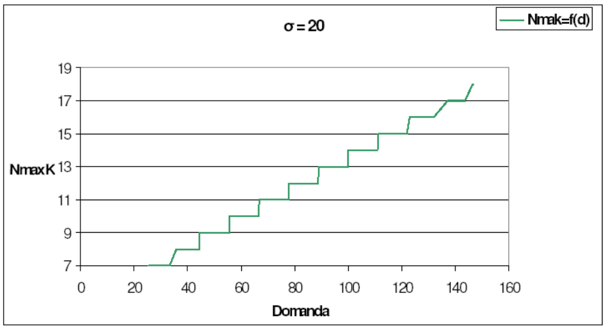

Fig. 2: Number of Kanban variation based on the defined value of demand variance (20).

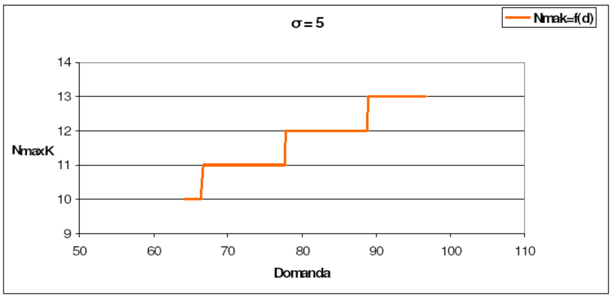

Fig. 3: Number of Kanban variation based on the defined value of demand variance (5).

After the analytical considerations, we focus around one of the factors examined: the demand. The choice is due to the consideration that the most critical situation is represented by a fluctuating demand which tends to have serious implications on the entire production system. For these reasons the attention will be focused only on the demand variation: we evaluate the dynamics of the system dimensioning in relation to the exogenous variations coming from the market.

IV. Problem Formulation

The problem of a variable demand in a Kanban cell has been studied and analyzed using the simulation software, based on the System Dynamics approach, Powersim Studio 5, which has the following advantages:

- Compatibility with Microsoft Excel and SAP;
- Possibility of generating scenarios even without knowing the structure of the model;
- There is an extensive library of mathematical functions to simulate the dynamic behaviour of complex variables.

A Kanban controlled systems can be seen as a set of cells. The communication between cells and within the cell is guaranteed by the information flow that Kanban create in the production system. In this work the focus is on a single work cell; the production system, in fact, may be seen as a replication of the cell for a number of times proportional to the size of the plant. The main actors of the process are production and assembly, respectively supplier and customer, and they identify a loop through which the Kanban flow with products. In this context, the assembly has the simple function of representing the customer's demand. The logic is a pull-kanban, so the production rate will be regulated by the customer demand (i.e. the assembly cell). The demand for the product will change according to a statistical distribution.

The system produces a single type of parts that are manufactured in the production department and sent to the assembly for shipment to the customer. The two variability and the implementation of any control measure of this variability, which in this case is found in the size of the buffer. The sizing problem of the system covers several aspects:

- the size of the production batch of the upstream section, which must take into account the capacity of the facility;
- the initial buffer size;
- the board size.

In this system there is a number n of Kanban cards called "virtual" because they are not part of tags available on the board. The introduction of virtual kanban "speeds up" the production, acting as an additional power supply.

V. The Model Assumption

The assumptions of this model are:

- the production department consists of one machine;
- the annual demand affects a single product;
- the production system is open 12 months a year, four weeks a month from Monday to Friday;
- the demand is a random variable distributed according to a normal with average of 80 pcs/wk and standard deviation of 12 units/wk and it has a weekly basis;
- the demand values are already free of any scrap;
- the demand arrivals are independent;
- the failure rate is assumed to be zero;
- the setup time is negligible;
- the moving time from the production department to the supermarket consists of 1 week;
- the production in the ahead department employs 1 week;
- between the two departments there are two accumulation zones of pieces: on board of the department, and in the input and output buffer, respectively;
- each container has a capacity of 100 pieces;
- raw materials supply in not a issue;
- the supermarket is sized based on the maximum size of board, in order to maintain the stock fewer products;
- the customer demand (represented by the demands of the assembly) is generated at the beginning of the week and this request must be immediately satisfied (no backorders are allowed).

In this paper the kanban board sizing is complicated by demand variability. The demand variation has an impact on the number of kanbans calculation, making the sizing capable of optimization.

The maximum size of board is given from the maximum value that the formula for the calculation of kanban returns in relation to the maximum demand peak recorded (Fig. 2). And this value, based on the Eq. 1 is equal to 15 kanbans.

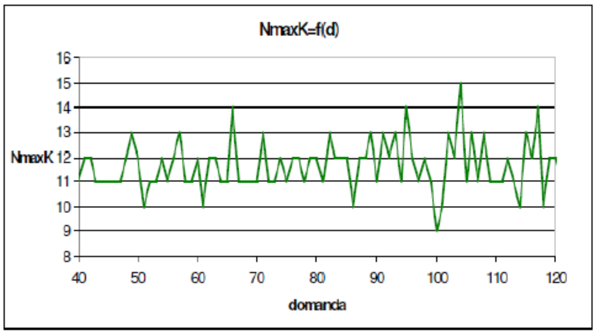

Fig. 2: Board sizing according to fluctuations in demand

VI. The Simulation Model

The first phase of the model construction is to determine the level and flow variables which characterize the system.

The stock variables are: the input buffer, the output buffer, WIP, idle time and stock out.

The flow variables are:

- production rate;
- demand rate;
- flows of parts from the machine to the buffer;
- supermarket flow management;
- idle time rate;
- stock-out rate.

The performance parameters are:

- total WIP;
- the input and output buffer levels;
- stock out rate;
- idle Time rate.

Furthermore, it was initially started with a simple model that describes the behaviour of the pull-kanban dedicated cell; then the model has become more complicated by introducing the variability of demand and it was defined a solution to mitigate this variability.

Each of these situations has been described using a specific simulation model. The starting point for the simulation is the creation of a basic model, which represents the operation of kanban production system under stable conditions. When production is stopped, the board sizing is based on stock quantities: the initial buffer size and the minimum batch production, respectively are equal to 100 pcs/wk and 80 pcs/wk.

This system is characterized by stable demand (40 pcs/wk). In this situation the system produces the production lot, but this happens only when the stock materials replenishment order comes from the supermarket. In this way we have overproduction that assure flow from stock-outs, but at the same time there will be costs. In this system it is possible to define the production plant in relation to the product demand; infact in these conditions, the demand is constant and then is possible to produce only when the client requests. The probability of stock out or that the production unit is idle is very low.

It is easy to understand that such situation is desirable but not cost effective.

In order to simulate the behaviour of a more realistic system, the constant demand was replaced with a normal probability distribution, with mean and standard deviation known (Fig. 3)

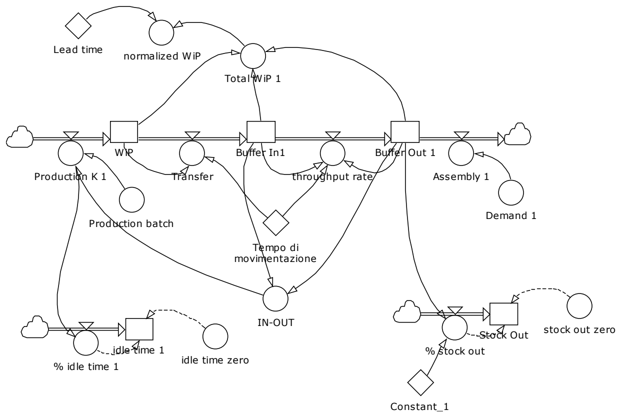

Fig. 3: Simulation model based on normal demand variation

This situation the system is no longer stable, but instead it is characterized by fluctuations around the average of the product demand.

In terms of variability the upstream production department may not be able to meet customer demand, because starting from the initial conditions the system demand varies around its mean. These oscillations affects on the system are showed in Fig. 4, where the data for this simulation model are compared with the performance achieved in the first case.

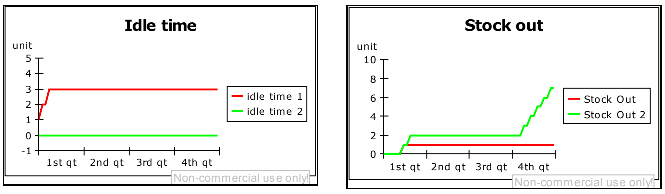

Fig. 4: Analysis of the performance in the first and second model: the comparison from idle time and stock out.

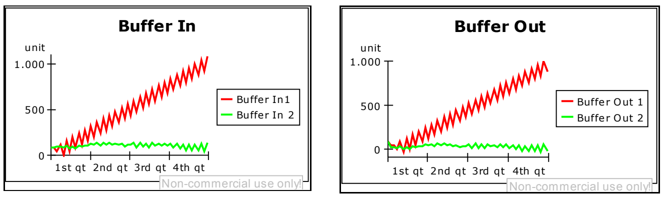

Fig. 5: Analysis of the performance in the first and second model: the comparison from in and out buffer.

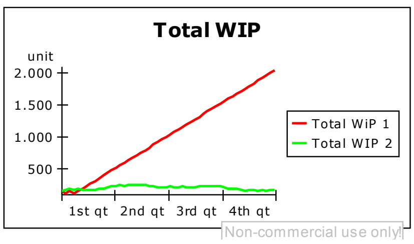

Fig. 6: Total Work in Process in each model.

From the previous figures can be seen:

- when demand is stable there are periods when production stops (and increased idle time), while when demand is variable the production is always active, and this confirms that in kanban systems demand gives the production rhythm;
- when demand fluctuates the production is forced to work faster. At the same time, however, the fluctuation in demand increases the risk of stock out, because production is not able to react quickly to the variation of products demand;
- in a kanban system the upstream department does not stop if the downstream always pulls the products;
- overall, the work in process are the sum of stock quantities and the products that waits to work near production lines. The total WIP in the system, however, strongly depends on the buffer levels: when demand is steady, buffers fills up more quickly and the total WIP levels increase; when the demand "pulls" more products following a normal or random distribution law, buffer levels remain relatively low, even by lowering the total WIP levels in the system.

The product demand is an exogenous variable, whose behaviour is unpredictable. You can not predict the amount of products that will be required to the system at a given time interval and then the system does not react to demand fluctuations.

VII. The New Assumptions

To implement kanban board in the systems characterized by variability, it is important to consider some "strategies" that must be examined to make the system able to operate in a more dynamic environment.

Therefore, a third model was made (Fig. 7). The starting operating conditions are the same, as well as the buffers size and minimum lot size to the initial time period.

In this model there is a new type of kanban signal, defined as virtual kanban.

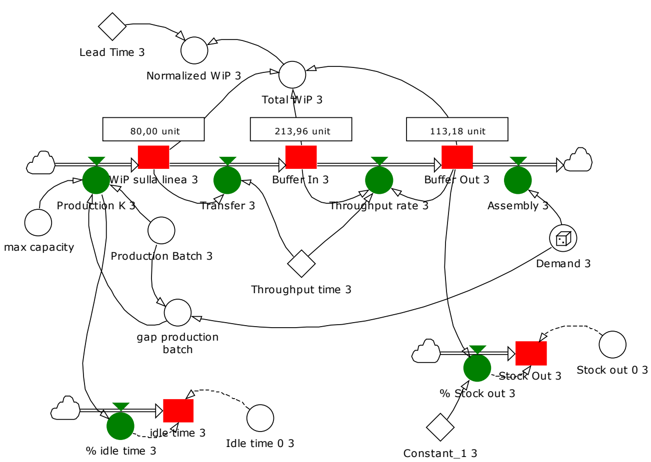

Fig. 7: The model with Virtual Kanban.

These “new kanban signal” can be introduced suitably into the system i.e. when it is considered necessary to the upstream department. The production of the upstream department is pulled by the kanban cards or signals; when the demand exceeds the minimum lot size, it means that the production kanban cards have not yet completed their cycle within the cell and therefore they are not yet available on kanban board to start the production cycle, this situation produces a delay that causes, probably, stock out.

It is assumed the following scenario: when demand exceeds the production lot, it is possible to increase the number of the system cards introducing some special cards, the virtual kanban, to allows the start of production in advance. In particular, this simulation model determines a number n of Virtual Kanban equal to the gap that exists between demand at time t and the minimum lot size at time t-1.

This means that the production, in those scenarios, varies in the same way of demand. In Fig. 8 it is possible to see that the production follows the demand only for values that exceed the minimum lot size. If the kanban level decreases in the demand variability we could have a sudden improvement that is fake, in fact the stock decrease and we could verify catastrophic consequences later if demand was to increase suddenly, causing immediately a stock out.

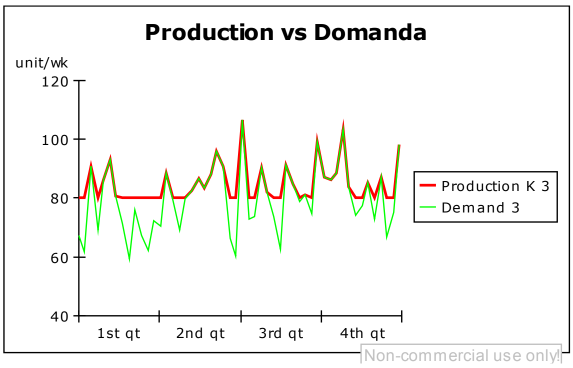

Fig. 8: Production rate based on the demand variability in the third model.

Finally, we must specify that the introduction of virtual kanban mechanism is governed by the operators of the line, following TPS philosophy. The kanbans, reached downstream cells will be collected in dedicated kanban boards, and sent back upstream to determine a scheduled replenishing logic, so they are always available when necessary.

It is noted that the virtual kanbans are not considered in the board sizing, in fact virtual kanbans don’t represents, physically, production lot. The next figures shows the system performances compared to the performances of the previous two models.

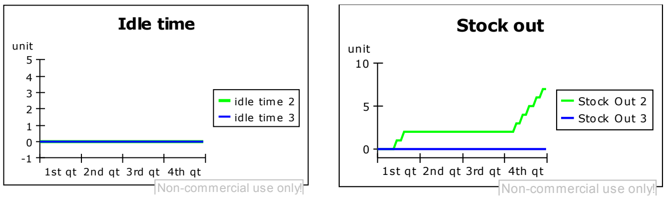

Fig. 8: Graphic summery of the performance parameters: comparison between model 2 and 3 (Idle Time and Stock Out).

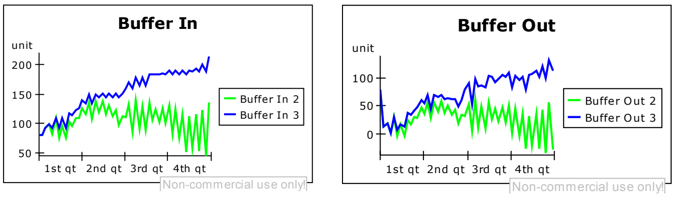

Fig. 9: Graphic summery of the performance parameters: comparison between model 2 and 3 (Buffer In and Buffer Out).

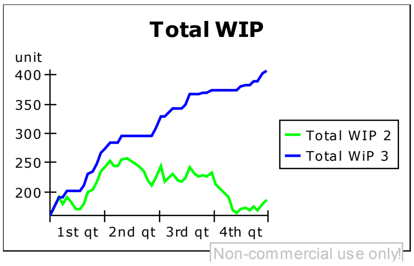

Fig. 10: WIP comparison between two models: without virtual kanban (green line) and with virtual kanban logic (blue line).

VIII. Conclusion

This work shows the characteristics of the kanban production system and the implementation in the manufacturing systems.

The aim of this paper was to study the demand variability in a pull kanban systems, represented in this paper as sets of kanban cells that are suppliers or costumers of other cells.

So the aim of this work was the adoption of a methodology more complete and likely to develop the knowledge of each individual subject. The simulation model proposed as a strategy to support the analysis and resolution of the demand variability has some advantages:

- the introduction of Virtual Kanban ensures that the system never goes stock out;
- the production units are increasingly active, the production flow is continuous.

At the end, it is possible to say that the experimental results obtained, in this first step, showed that the constructed model can be used as a valid tool for strategic decision support for manufacturing systems (with the assumptions made for the model) that want to be able to react appropriately to the variability of the market using a pull logic.

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