# A system dynamics modelling, simulation and analysis of production line systems for the continuous models of transfer lines with unreliable machines and finite buffers

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Abstract

Serial production lines are a fundamental type of production system of great importance. When the line is mechanised, both machine breakdowns and interstage storage can significantly affect the efficiency of a production line. Machine breakdowns can cause line stoppage. Interstage storage helps to provide material for downstream machines in the event of a machine breakdown, and thus reduces the adverse effect of machine breakdowns. Despite an extensive research literature on the design and analysis of production line systems, analytical models and results for studying the effect of machine breakdowns and interstage storage remains limited. With rapidly increasing complexity in studying large systems, a new approach based on the system dynamics for modelling, simulation and analysis of such systems is proposed. Our system dynamics model reflect the essential features to be found in typical plant configurations and allow us to consider the expected throughput of material under different operating policies.

## Introduction

Many typical industrial plants are very complex in nature. They tend to consists of processing stages (or units) together with buffer stocks (or tanks) with many or all of the units being subject to failure. Also, it quickly becomes apparent that units cannot always be operated independently of one another due to the presence of full or empty tanks which necessitate adjustments to flow-rates. A complete description of a particular plants is seen therefore, to depend on many factors. These can include such aspects as the nature of the chemical processes involved, a detailed operating policy to be employed in respect of the plant, details of planned maintenance sessions and so on. Thus, it appears that any attempts at modelling individual plants are likely to falter if we seek to include all aspects of the particular plant involved. The resulting model would be so complex as to be intractable.

We therefore set up simplified models which aim to reflect the essential features to be found in typical plant configurations. We concentrate our attention on such aspects of plant behaviour as the failure and repair characteristics of units, capacities of tanks and maximum operating rates of units.

## Methods of analysis

The two principal approaches which have been employed to date in the solution of the type of model under consideration are the analytical approach and the simulation approach. Other approaches have been advocated by Cheng (1972), Cheng and Jones (1981,1983) and Jones (1987). However, these will not be discussed in any detail in this paper as we propose to concentrate on the simulation approach.

The analytical approach proves to be very difficult for all but unrealistically simple models. By the very nature of the solution method, each model has to be treated individually so that such minor changes as the introduction of new parameter values means that a completely new analysis has to be undertaken. Thus, even though several authors have discussed this approach, particularly in the context of optimal control, few examples appear in the literature.

The simulation approach, on the other hand, is a well tried method which is capable of giving excellent results.

The model to be considered in this paper consists of just two processing units (UNITS) together with a finite storage facility (TANK), arranged in series as shown in Figure 1.

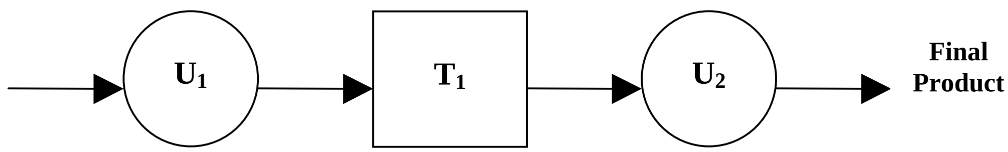


Fig. 1. Single-tank series production system

Clearly this is a very simple model and few industrial processes can be represented as simply. However, it is easy to see that quite complex manufacturing plants can be represented realistically by using the model of Figure 1 as a building block; networks of such elements, involving series, parallel and branching components, can be established and, given a suitable development environment, simulated.

Units

A unit may be subject to failure in which case it must be repaired or replaced. This means that at any given time t, a unit may be working, or capable of working, or it may have failed and be undergoing repair. Thus, we may think of a particular unit as being in one of two states, working or failed. We therefore refer to a unit which is working as being UP, or in state 1; a failed unit is said to be DOWN, or in state 0.

We assume that a unit $U_i$ has a maximum possible workrate, or rating, $\alpha_i$. Then at some time t, its actual workrate $r_i(t)$ will satisfy the inequality $0\leq r_i(t)\leq\alpha_i$. We note that $r_i(t)$ can be zero either due to $U_i$ being down or because of congestion downline of $U_i$; for example a tank may be full and a unit may have failed so that we must set $r_i(t)=0$. Similarly, we may need to set $r_i(t)<\alpha_i$ in order to balance input and output in respect of a tank which is empty or one which is full, depending on the ratings of the units. Finally, we need to know something concerning the failure rate of a unit $U_i$ and also the time to repair of a failed unit. Thus, we define

$$P(U_i \text{ fails in } (t, t + \delta t)\ |U_i \text{ up at } t) = \mu_i\ \delta t + o(\delta t)$$

$$P(U_i \text{ up in } (t, t + \delta t)\ |U_i \text{ up at } t) = 1 - \mu_i\ \delta t + o(\delta t)$$

and for a unit which is down at time t

$$P(U_i \text{ has repair completed in } (t, t + \delta t)\ |U_i \text{ down at } t) = \lambda_i\ \delta t + o(\delta t)$$

$$P(U_i \text{ repair is not completed in } (t, t + \delta t)\ |U_i \text{ down at } t) = 1 - \lambda_i\ \delta t + o(\delta t).$$

These definitions, together with the probability of two or more events occurring in (t, t + $\delta$t), ensure that failures occur according to a Poisson process and that time to repair follows a negative exponential distribution.

Tanks

Each tank $T_j$ has a finite capacity $K_j$. At any time t, the level of fluid in the tank, $S_j(t)$ say, will satisfy the inequality $0 \leq S_j(t) \leq K_j$. Clearly, the tank may become empty or it may become full. When either of these states occur, it will be necessary to adjust the workrate of units connected to the tank.

The problem

Our objective is to consider the expected throughput of material under different operating policies. One such policy could be to run all units at maximum possible rates at all times. Clearly, we must be interested in such quantities as the distribution of stock level in the tanks and also the availability of units.

**The analytical approach**

The model shown in Figure 1 has been considered analytically by a number of authors since the early 1960s, starting with Finch (1961) and Miller (1963). There have subsequently been papers by Cheng (1972), Fox and Zerbe (1973), Murphy (1975, 1978, 1979), Henley and Hoshino (1977), Wijngaard (1979) and more recently Malathronas *et al.* (1983), Jones (1987), Hillier and So (1991) and Alvarez-Vargas, Dallery and David (1994).

These researchers have approached the problem from differing standpoints and often some of them appear to have been unaware of existing results obtained by other workers in this field.

For example, Fox and Zerbe adopt an operating policy which can be described as “tank-full”; that is, the workrates of the units are arranged in such a way that the tank always remains full. Others adopt a “do nothing” policy which means that both units are run until one fails or the tank becomes full or empty when some action must be taken. Malathronas *et al*. remark that the latter policy produces a larger expected output than the “tank-full” policy and is the more realistic of the two. It would appear that they are unaware of the result due to Cheng (1972) which establishes the “full-on” policy. This means that all units are operated at the maximum possible rate at all times. This is the optimal policy for line-tanks models [see Cheng (1972)]. The line-tanks models are a network configuration consisting of units and tanks such that every tank has only one input unit and also outputs to just one unit [see Cheng (1972)].

The various analyses undertaken highlight the complexity of the analytical approach for this simple model. They all deal with the steady-state solution which tends to be obtained under simplifying assumptions such as equal ratings, equal failure rates or equal repair rates of the units.

Jones (1987) has discussed in detail the transient case and its complexity is such that there is little virtue in reproducing any detail here. Suffice it to say that the solution for stock level alone involves the solution of a set of four simultaneous partial differential equations of the type found in single-server queue theory. Further, if any of the relationship between ratings are altered the equations to be solved will also alter. That is, each case must be considered on its merits.

We therefore proceed to consider simulation approach but before doing so we remark on the various events which affect the operation of the system. They are the failure of  and completion of repairs to units, together with the tank becoming full or empty and these are the features we must incorporate in our simulation model. Finally, we indicate in Figure 2 some typical behaviour patterns of stock level with the passage of time.

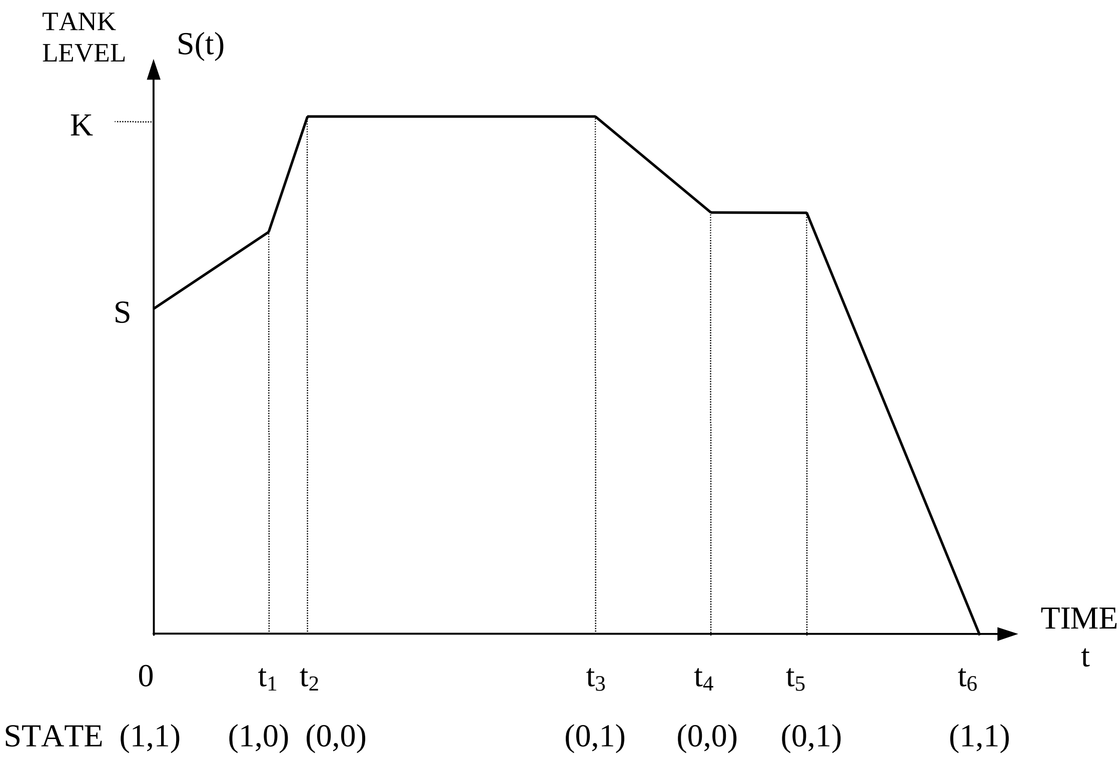


Fig. 2. The distribution of stocks

As can be seen from Figure 2, it is possible for the stock level to have the values zero and K, that is for the tank to be empty or full respectively, for significant periods of time.

## The POWERSIM$^{TM}$ Model

The interface is shown in Figure 3, together with an example of a very simple system. The similarity of the example to the conceptual model of Figure 1 shows that, POWERSIM$^{TM}$ (Copyright © 1994 - ModellData AS) promises to be a very useful modelling device for systems such as those which have been described earlier in the paper.

Powersims application window displays the menus and provides the work space for any document used within the application.

Fig. 3. User Environment in Powersim - showing the basic structure of Unit-Tank-Unit model

The completed model, as a structural diagram, is shown in Figure 4a. The expected throughput of material under the ‘full-on’ policy that is to run all units at maximum possible rates at all times is shown in Figure 4b.

## Concluding Remarks

Experience with POWERSIM™ has shown its unrivalled usefulness as a development tool for modelling and simulation of production systems. The ability to debug and verify a model on-line, gaining a feel for how the modelled system behaves, contributes greatly to the modeller's understanding. It is felt that it would be particularly fruitful to carry out participative development together with an industrial client using the interactive environment.

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