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Dynamic Modeling and Stability of the Reconfiguration of Manufacturing Systems

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ABSTRACT

Reconfigurable Manufacturing Systems (RMS) are designed with certain key characteristics such that they can be upgraded in response to market demands. The upgrading of the system can be in terms of either capacity (volume of parts that can be produced on the line) or functionality (number of different types of parts that can be produced on the line). In other words, an RMS can provide exactly the capacity and functionality needed, exactly when needed. The complex nature of RMS and the need for a reconfiguration policy requires the development of a model to assist manufacturing engineers to implement the optimum reconfiguration policy. A fluid dynamic system analogy for RMS, using a control-theoretic approach, is developed, and several concepts and ideas of RMS such as reconfiguration and its relationship to scheduling are demonstrated using this analogy. This analogy is the basis for a dynamic model which characterizes the reconfiguration policy and the production scheduling of an RMS. We also develop and analyze a useful simplified dynamic model of a production system whose capacity and/or functionality can change over time. It is shown, based on the simplified model that there are conditions for stability that depend on the time delay (T) associated with implementing the changes in the production system, and on a gain (K) reflecting the rate of reconfiguration. A measure of performance is developed to quantify the potential benefits of RMS over traditional dedicated or flexible manufacturing systems that have fixed capacity and/or functionality. The results of this analysis show that for changes in capacity and/or functionality to be effective, the product of the delay (T) in responding to market demand, and the rate of reconfiguration (K), must be bounded.

INTRODUCTION

Manufacturing of consumer goods has consistently accounted for over 20% of the gross domestic product, and is the foundation of the US economy. But to stay competitive in the 21st Century, manufacturing companies must possess a new type of manufacturing system that is very responsive to global markets; a system whose production capacity is adjustable in response to fluctuations in product demand, and which is designed to be upgradeable with new process technology needed to accommodate tighter product specifications. Current systems, even so called flexible manufacturing systems, do not have these characteristics. Today's world market requires a change in the existing manufacturing systems [NAP 1998]. Cost-effective, reconfigurable manufacturing systems, whose components are reconfigurable machines and reconfigurable controllers, as well as methodologies for their systematic design and diagnosis, are the cornerstones of this new manufacturing paradigm termed "reconfigurable manufacturing" [Koren and Ulsoy, 1997].

By definition, a Reconfigurable Manufacturing System (RMS) is one designed at the outset for rapid change in its structure, as well as its hardware and software components, in order to quickly adjust its production capacity and functionality in response to sudden, unpredictable market changes as well as introduction of new products or new process technology. Components may be machines and conveyors for entire production systems, mechanisms for individual machines, new sensors, and new controller algorithms. New circumstances may be changing product demand, producing a new product on an existing system, or integrating new process technology into existing manufacturing systems.

An RMS aims to enhance manufacturing responsiveness in the production of low-cost and high-quality products. Such manufacturing systems do not exist today. Most manufacturing industries currently use a portfolio of dedicated manufacturing lines (DML) and flexible manufacturing systems (FMS) to produce their products. Dedicated manufacturing lines, or transfer lines, are based on fixed automation and produce the core products of the company at high-volume. Each dedicated line typically produces a single product. Flexible manufacturing systems produce a variety of products on the same system. They consist of computer numerically controlled (CNC) machines, robots, and other programmable automation. The production capacity of FMS is usually lower than that of dedicated lines and they are more expensive.

The common denominator for DML and FMS systems is that they use fixed hardware and fixed software. For example, only part programs can be readily changed on CNC machines, but not the core software nor the control algorithms. During the last few years, however, two enabling technologies for RMS have emerged [Mehrabi and Ulsoy, 1997]: modular, open-architecture controls that allow reconfiguration of the controller [Koren 1997], and modular machine tools that allow reconfiguration of the machine hardware [Kota, 1997]. These emerging technologies show that the trend is toward the design of systems with reconfigurable hardware and reconfigurable software with modularity as a key characteristic.

We can expect, in the near future, that RMS will join DML and FMS in the mix of systems that manufacturers use. When market fluctuations, market uncertainty, and rapid product changes are considered, there are strong economic arguments for the development of such systems [Birge 1998]. RMS will be open-ended, so that they can be improved and upgraded rather than replaced. They will allow flexibility not only in producing a variety of products, but also in changing the system itself. Reconfigurable systems will not be more expensive than flexible manufacturing systems, or even dedicated manufacturing lines since, unlike DML or FMS, the RMS is installed with exactly the production capacity and functionality needed, and may be upgraded in the future, exactly when needed.

Fig. 1 shows that dedicated manufacturing lines typically have high capacity but limited functionality. They are cost effective as long as demand exceeds supply. But with saturated markets and increasing pressure from global competition, there might be situations where dedicated lines do not operate at full capacity. Flexible systems, on the other hand, are built with a high degree of flexibility and functionality, in most cases even with more than what is needed at installation time. The logic behind this is "to buy it just in case it may one day be needed." However, in such cases capital lies idle on the shop floor and a major portion of the capital investment is wasted. These two types of waste are eliminated with RMS. In the first case the RMS allows one to add the extra capacity exactly when required, and in the second case to add the additional functionality exactly when needed. What distinguishes RMS from either the traditional DML or FMS is the fact that its capacity and functionality change over time in response to market demand. There is an important distinction between the traditional DML, FMS, and RMS. The difference lies in their decision making process which is involved in their operations. One important decision at the outset of installation of DML and FMS on choosing the parameters and characteristics of the system is required, and they do not require any other critical decisions or designs beyond scheduling during their operation. In contrast, in an RMS a series of decisions needs to be made for the system to reconfigure itself to respond to the market demands. These series of decisions characterizes the reconfiguration policy, and it makes the system more complex to operate relative to DML and FMS. The research presented in this paper is a basis for a model which characterizes the dynamic nature of RMS, and can be used as a tool to assist of manufacturing engineers to implement the optimum reconfiguration policy. Reconfigurable manufacturing systems are generally more complex to operate than the traditional DML and FMS. However, there has not been any theoretical work available to study their behavior. A recent work [Kusiak 1999] has considered scheduling problems in an RMS. However, no models have been developed to characterize the dynamics of reconfiguration.

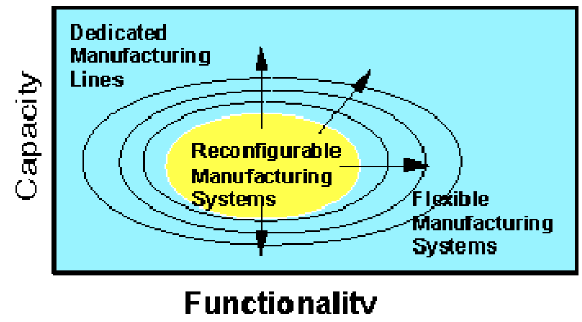

Figure 1: Types of manufacturing systems in terms of capacity-functionality.

The purpose of this paper is, for the first time, to mathematically model and analyze the change with respect to time in capacity and/or functionality that characterizes reconfigurable manufacturing systems. In the next section of the paper we present a fluid dynamic system analogy to reconfiguration of an RMS. This analogy helps to understand the important keys in reconfiguration and scheduling. A simple differential equation model is then developed based on the effects of reconfiguration, and an analysis of its stability properties is presented.

MODELING AND ANALYSIS

A Dynamic Systems Analogy and Simulation Model for RMS

A fluid dynamic system analogy to reconfiguration of an RMS is presented in this section. This analogy helps

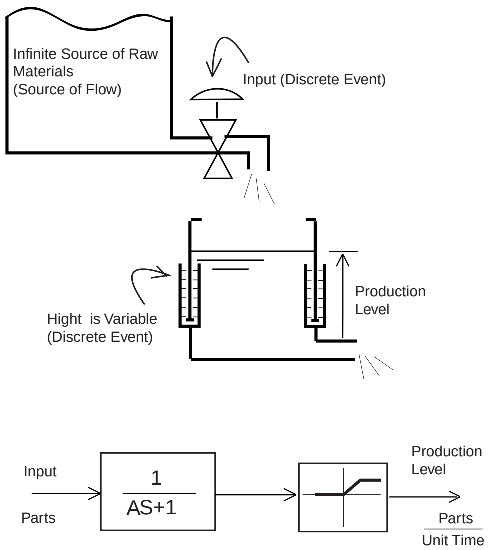

Figure 2: A fluid dynamic system analogy for RMS and its block diagram.

to understand the concept of reconfiguration in RMS and distinguish it from scheduling in terms of capacity and functionality. A simple tank as shown in Fig. 2 models the manufacturing line. The input flow to the tank represents the raw material entering to the manufacturing line, and the level of fluid in the tank represents the production level in the manufacturing system which can vary by changing the rate of raw material entering to the system. The volume of the tank, which is the product of its cross section area by its height, represents the capacity of production in the manufacturing line, which is considered variable by changing the height of the tank as shown in Fig. 2. For simplicity in modeling, without loss of any generality, the cross section area of the tank is considered to be one unit, therefore, the height of the tank represents its capacity. The outflow of the tank shows the production and accumulating (integrating) the production using proper coefficients gives the profit or revenue generated by the manufacturing system. We assume certain properties and limitations for this fluid system model; there can be only incremental changes of inflow to the tank, in other words, the input to the tank is a discrete event input. The cross section area of the tank is constant and its height is variable and the variations take place only in a discrete event nature as shown in Fig. 2. The equivalent block diagram for the manufacturing line is also shown in Fig. 2, and the saturation element models the saturation of the fluid in the tank which happens when the fluid level (production level) passes the height (capacity) of the tank. It should be mentioned here that this model is just a simple analogy to understand the concepts of reconfiguration and a more exact model is needed to describe the behaviour of every individual manufacturing system. The concepts of reconfiguration and scheduling in manufacturing systems and their differences can be modeled using the fluid system analogy presented here. Fig. 3(a) demonstrates the analogous concepts of reconfiguration and scheduling in the fluid system. The fluid level (production level) is measured and compared with the market demand. An adjustment needs to be made based on this comparison. Let's assume that the fluid level (production level) should be increased, because the market demand requires it to do so. Apparently, the proper way to increase the fluid level (production level) is to increase the input flow to the system (or increase in the raw materials to the manufacturing system). This approach which will naturally increase (or decrease) the fluid level (production level) in the system is analogous to scheduling in the manufacturing lines. Scheduling in the system can adjust the fluid level (production level) only if the market demand does not require the fluid level (production level) exceed the height (capacity) of the system. In that case, the height (capacity) of the system should change first to avoid saturation. This process which adjusts the height (capacity) of the system is analogous to the reconfiguration in terms of capacity in manufacturing lines.

Reconfiguration in the manufacturing line always requires a series of critical decisions (reconfiguration policy) which should be made based on some economic factors to make sure that the benefits of reconfiguring the system exceeds the cost of changes and loss of production during the ramp-up period and the delay time involved with the reconfiguration. The ramp-up period is the time needed to reach the quality production level in the manufacturing line after restarting the reconfigured system. The time delay involved in the reconfiguration consists of the time which the decisions should be made, and the time which the changes should be studied, designed and implemented to the system. These characteristics of RMS are depicted in the block diagram model for the analogous fluid dynamic system in Fig. 3(b). As shown in the figure, market demand is compared to the production level and the maximum capacity of the system at the same time. Based on this comparison, a decision is being made to choose between scheduling and reconfiguration. These series of decisions characterize the reconfiguration policy. The decision making process is simply modeled by a piecewise linear step function here as shown in the figure. If the decision is to continue the scheduling rather than reconfiguration, then the scheduling loop is activated and tries to adjust the production level (fluid level) to follow the market demand. When the market demand exceeds the current capacity of the system, based on the profit loss of not having the sufficient production level and economic factors, a decision will be made to start reconfiguration. This will turn the scheduling switch off, and initiate the reconfiguration process. After a time delay, which is represented by e^{-sT}, the system is

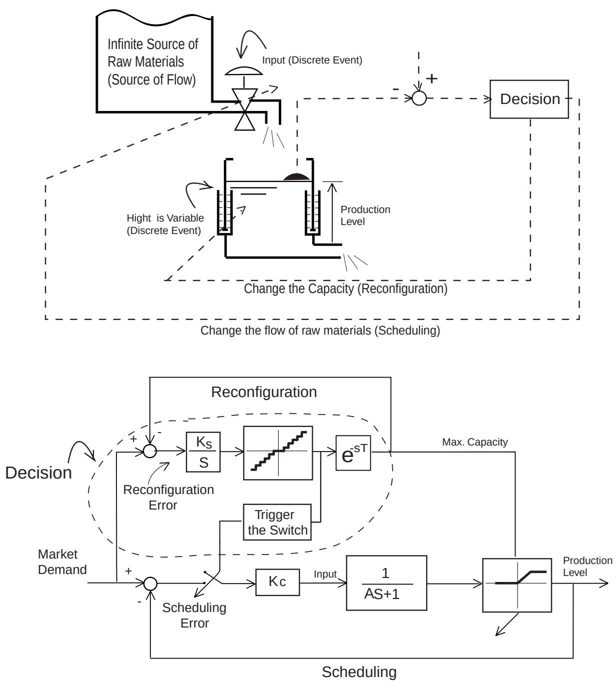

Figure 3: Process of reconfiguration and scheduling for the fluid equivalent system.

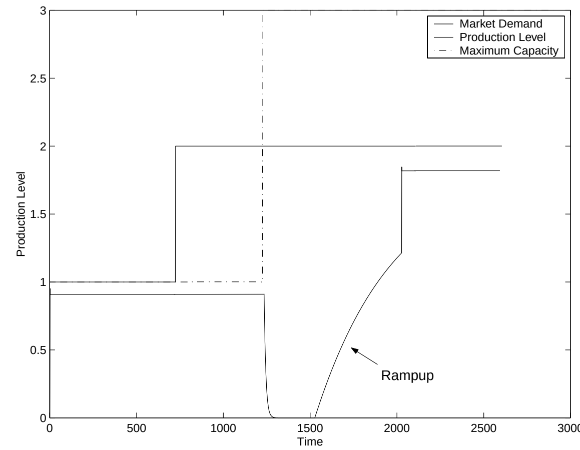

Figure 4: Reconfiguration in a Reconfigurable Manufacturing System.

reconfigured and by following a ramp-up period, it will follow the market trend with the new capacity level.

To show the concept of this analogy, a simulation is presented in Fig. 4 to illustrate the scheduling and reconfiguration in a manufacturing system. This simulation is performed based on the block diagram presented in Fig. 3(b). The market demand is considered to be a step signal that shows a double increase in the market demand after 750 time increments. The initial maximum capacity of the manufacturing line is considered to be 1 unit, and the production level is a bit less than the capacity of the system. After 750 time increments, the market demand increases and it consequently requires a reconfiguration in terms of capacity of the system. Not being able to supply enough production to the market and loosing profit and competitiveness as a result of that, requires a decision to reconfigure the manufacturing line.

The decision making process must consider the economic factors of the market, and it takes 500 time units to be made in this simulation. At this point, the scheduling switch goes off and the production level shuts down. The decision is to increase the capacity of the system from 1 unit to 3 units, and there is some time involved for reconfiguration to make the necessary changes in the system to achieve the new capacity level. The time needed to make the changes characterizes the time delay for reconfiguration. After the changes in the system are made, the ramp-up period will start which shows a slow dynamics because of its nature. At the end of the ramp-up time, the system will perform normally and follow the market trend. Reconfiguration in manufacturing systems takes place in terms of capacity and functionality. Reconfiguration in terms of functionality corresponds to two different cases in a manufacturing line. The first case is when a change in the type of production is needed, and as a result, a conversion in the production line takes place. The second case is when there is a need to decrease the production capacity in one line and add it to another line to increase its capacity at the same time. The first case is also referred as conversion, and the second case is just referred as changing in functionality. The analogous fluid system model for the three different cases of reconfiguration are shown in Fig. 5.

The concept of reconfiguration in terms of capacity is shown in Fig. 5(a), and as shown in the figure, height of the tank is increased to have more capacity in the manufacturing line through reconfiguration. Fig. 5(b) shows a manufacturing line which produces two products A and B. Changing the functionality of a production line is changing the functions of some hardware in the manufacturing line and making them to produce a different product. In other words, changing the functionality is decreasing the capacity in one line and adding it to another one. This figure shows a two tank equivalent fluid system which represents the production of two productions A and B. Changing the height of the tanks represents the change in functionality which decreases the capacity in one tank and increases it in the other one keeping the total capacity constant. Conversion is modeled using the same equivalent fluid system as shown in Fig. 3(c), and it takes place by changing the raw materials entering to the manufacturing line B to produce production C.

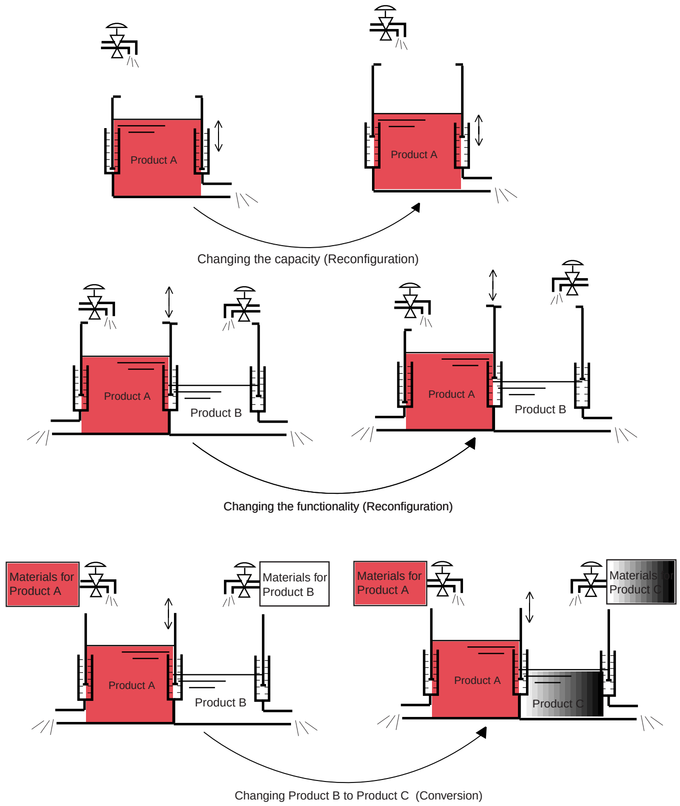

Figure 5: Reconfiguration concepts in fluid analogy.

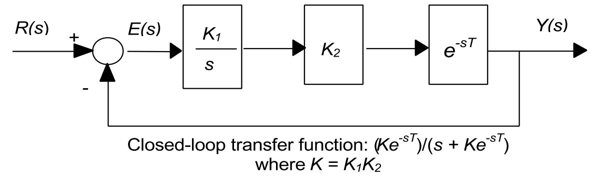

Figure 6: Block diagram of the dynamical model for RMS capacity.

Symbol	Units
t, T	time (eg. year,week,day)
$y(t), r(t), e(t)$	Number of parts / Unit time
K_1	\$/Part
K_2	(Number of Parts/ Unit Time)/\$
$K = K_1K_2$	1/Unit Time

Table 1: Summary of model variables and parameters and their units.

A Simplified Model for RMS

Here we present a simple dynamical model for the reconfiguration in terms of capacity of a manufacturing system assuming that the effects of scheduling can be neglected in the dynamics of the simplified model. The effects of scheduling in the system can be assumed to be very small because the dynamics involved with scheduling is very fast comparing to the dynamics of reconfiguration. The block diagram presented in Fig. 3(b) can then be simplified to the block diagram presented in Fig. 6 which only depicts the effects of reconfiguration provided that the effects of scheduling are relatively rapid and can be neglected. Only the scalability is considered as the dominating factor. Another simplifying assumption, which is made here, is that the discrete event nature of the reconfiguration is considered to be continuous. This, without loss of any significant modeling characteristics, enables us to use simple continuous time and event differential equations.

Let $y(t)$ denote the capacity of a production system. Furthermore, y_0 is a nominal (constant) value of $y(t)$, such that $y(t) = y_0 + Dy(t)$. Given the model structure in the block diagram in Fig. 6, the differential equation for this model is given by,

$$\frac{dy(t)}{dt} = Ke(t-T) \qquad y(0) = y_0 \qquad (1)$$

where t is the time variable, $K = K_1K_2$, and $e(t) = r(t) - y(t)$ represents the error at time t. This error is the difference between the desired capacity, $R(t)$, and actual capacity, $y(t)$. When the market demand and the actual system characteristics are matched, then $e(t) = 0$, and the time derivative of $y(t)$ is zero. Consequently, the system capacity does not change. However, if $e(t) \neq 0$, then $y(t)$ is increased or decreased accordingly. The reconfiguration gain, K, represents how large a change in $y(t)$ can be made in response to an error. It is the product of two gains K_1 and K_2. The output of the $(\frac{K_1}{s})$ block in Fig. 6 gives the accumulated loss in dollars (\$), when K_1 has the units shown in Table 1. The system time delay, or dead-time, is represented by T. Clearly, both K and T will depend on the design of the manufacturing system being modeled, and our ability to reconfigure the system. When the delay parameter T is small, then we can respond to market demands quickly. The product $Ke(t)$ represents the rate of the change that can be made in y (i.e., capacity) in response to market demand. For a given error level, $e(t)$, then the change made is large when K is large.

The performance of the system can be measured using a metric based upon the error, $e(t)$. For example, the integrated absolute value of error (IAE) performance index is given by,

$$J = \int_{t_0}^{t_1} |e(\tau)| d\tau \qquad (2)$$

where t_0 is the initial time when the system is installed, and t_1 is the final time, representing the life of the system.

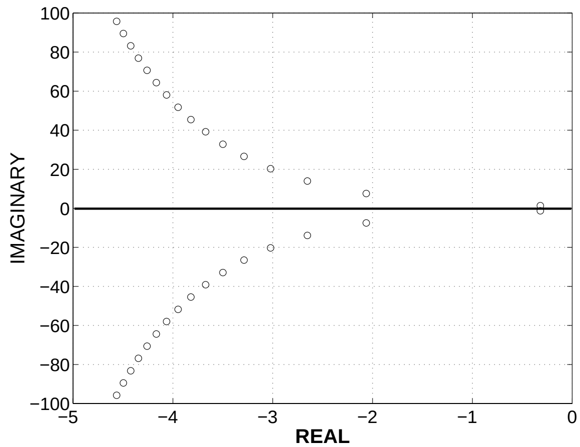

Figure 7: Roots of in the complex plane

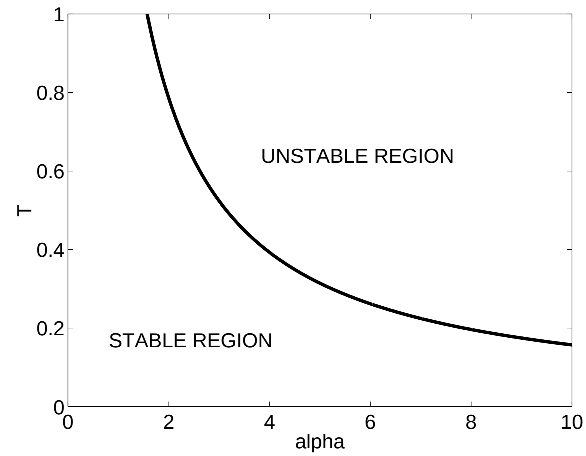

Figure 8: Stability Boundary in the K-T Plane.

Analysis Using the Simplified Model for RMS
The stability of the dynamical system in Eq.(1) can be determined by analysis of its characteristic equation:

$$s + Ke^{-sT} = 0 \tag{3}$$

This equation has an infinite number of roots in the complex plane, or solutions for s, when $T \neq 0$. For the system to be stable, the complex roots of this equation must not have any positive real parts. The first 32 roots for Eq.(3) where $T = K = 1$ are shown in the complex plane in Fig. 7 [Asl and Ulsoy 2000]. The stability boundary can be determined when the real parts of the complex roots are zero. Consequently, we can set $s = j\omega$ in Eq.(3), to obtain:

$$Re : K\cos(\omega T) = 0 \tag{4}$$

$$Im : \omega - K\sin(\omega T) = 0 \tag{5}$$

where we have used the Euler identity, . From (4), when $K \neq 0$, we must have $\omega T = (\frac{\pi}{2}), (\frac{3\pi}{2}), (\frac{5\pi}{2})$, etc. Using these values of ωT in (5), and selecting the most restrictive case (i.e., $\omega T = \frac{\pi}{2}$), gives the stability boundary $K = \frac{\pi}{2T}$, or,

$$T = \frac{\pi}{2K} \tag{6}$$

This is plotted in Fig. 8, and shows that the model predicts instability when the delay T or gain K become too large (i.e., for stability the product $TK < \frac{\pi}{2}$). Large delays T can only be tolerated when K is small, and vice versa. As an example, let's apply the above model and analysis to a simple production scenario. Consider a manufacturing line with a fixed capacity, $y = 250,000$ parts per year. This line produces only one type of product, and initially operates at full capacity. The demand for the product, however, changes over time as (see Fig. 9):

$$r(t) = \begin{cases} 250000 & t < 4years \\ 550000 & 4years < t < 10years \\ 900000 & 10years < t < 17years \\ 700000 & 17years < t < 25years \end{cases} \tag{7}$$

where t goes from 0 to 25 years and $r(t)$ is measured by parts/year. (a) When $K = 0$, the line is not reconfigurable, and the capacity remains at $250,000$ parts/year. Due to inadequate capacity, a market opportunity is missed, and a loss is incurred. This can be measured, using the performance metric in Eq. (2) with $t_0 = 0$ years and $t_1 = 25$ years, as $J = 9.95e^{+6}$. (b) If the line can be made to be reconfigurable, then the capacity can change to try to match the demand. If this is done such that $K = 1$ (1/years) and $T = 2$ years, then the reconfigurable system is unstable, and the error grows over time. The performance measure in Eq. (2) now yields $J = 1.43e^{+7}$. (c) If the line can be made reconfigurable, such that $K = 0.5$ (1/years) but $T = 1$ years, then the system is stable. This is accomplished by reducing the delay in responding to the market from 2 to 1 years and decreasing the reconfiguration gain from 1 to 0.5. The value of the performance measure is reduced to $J = 1.81e^{+6}$. This represents an improvement of nearly 6 times over the fixed capacity case, and of about 8 times over the unstable reconfiguration case in (b).

The results for these three cases, along with the capacity demand function $r(t)$, are shown in Fig. 9. What this simple example illustrates is that a reconfigurable system can respond to market opportunities that would be lost with a fixed capacity system.

Application to a Reconfiguration Scenario
We consider a 10 year long manufacturing scenario, where the demand for two products (Products A and

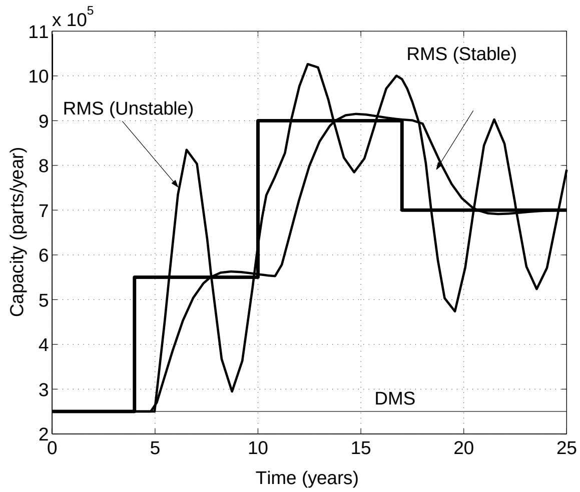

Figure 9: Numerical results for capacity versus time for the example.

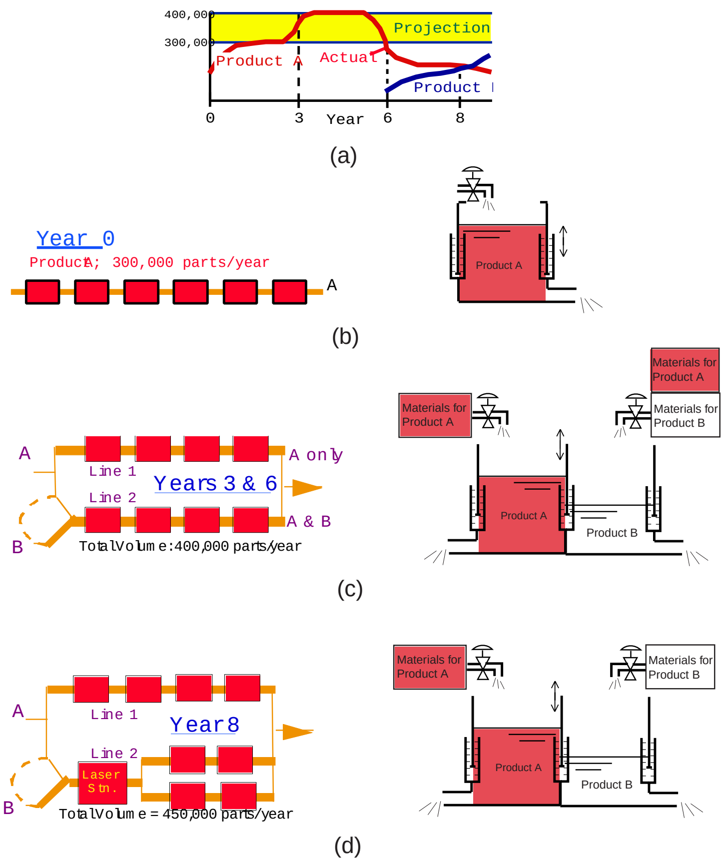

Figure 10: A Scenario Illustrating Reconfigurable Manufacturing.

B) changes over time as shown in Fig. 10(a). The projection for product A, at year 0, is between 300,000 to 400,000 units per year. The actual market demand rapidly increases to 300,000 in about one year, during years $3-6$ it increases to about 400,000 then falls off to a level of about 150,000 units per year. During years $5-10$ the demand for another product (Product B) goes from 0 to about 250,000 units per year. Product B is a new product that was not yet designed at year 0 when the manufacturing system was first designed and built. Figures 10(b) to 10(d) illustrate how a reconfigurable manufacturing system can respond to such a scenario by providing exactly the functionality and capacity needed, exactly when needed. Initially (i.e., at year 0), the RMS is designed to produce 300,000 units per year of Product A using a serial configuration of 6 stations or machines modeled by a single tank fluid system (see Fig. 10(b)). By year 3 the RMS is reconfigured for 400,000 units per year of Product A by adding two machines, reconfiguring some of the existing machines, and going to a system configuration of two parallel lines with 4 machines in each line (see Fig. 10(c)). This same RMS, by year 6, is modified such that Line 1 continues to produce Product A, while Line 2 can be rapidly converted, or switched, between production of both Products A and B. The fluid equivalent of these lines is a two tank fluid system with a conversion capability on the second tank to produce A and B (see Fig. 10(c)). In year 8, as the market demand for Product B continues to grow, Line 2 is now producing Product B almost exclusively and its capacity has been increased from 200,000 to 250,000 units per year by the addition of a new machine with advanced laser technology and through reconfiguration of the machines and machine configuration on Line 2.

The above scenario, together with an economic analysis, would illustrate the potential advantages of RMS.

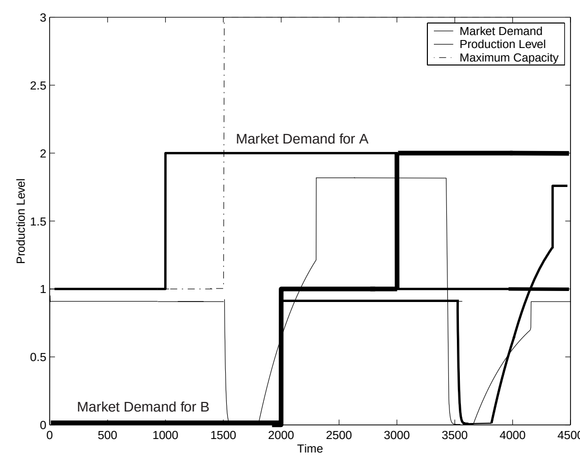

Figure 11: Simulation of the scenario Illustrating Reconfigurable Manufacturing.

However, the above scenario assumes throughout that the necessary level of reconfiguration can be done very quickly. Next, we perform a simulation to show the dynamics of reconfiguration associated with this scenario using our fluid dynamic model. Simulation results are presented in Fig. 11 assuming that the market demand changes are simplified as step functions. Market demands for A and B are changing as it is shown in the figure, and the capacity values for A and B are being reconfigured to follow the market demands.

SUMMARY AND CONCLUSIONS

Low cost and high quality products have historically been the main economic objective in manufacturing. However, global economic competition and rapid social and technological changes have forced manufacturers to face a new economic objective: manufacturing responsiveness. Consequently, a new type of manufacturing system, a Reconfigurable Manufacturing System (RMS) is needed.

Reconfigurable manufacturing systems represent an enhancement over current manufacturing technologies (i.e., dedicated manufacturing lines (DML) and flexible manufacturing systems (FMS)) in that they change the capacity and functionality of the production system in response to market demand. The new reconfigurable manufacturing paradigm requires development of systematic methods, and software tools, for the rapid design and build of manufacturing systems at both the system and machine level. The effectiveness of reconfiguration will depend upon the development of such tools.

This paper has presented a fluid dynamic system analogy for RMS and several concepts and ideas of RMS such as reconfiguration and its relationship to scheduling were demonstrated using this analogy. The analogy is developed due to the complex nature of RMS and its need for an RMS policy design algorithm to assist the manufacturing engineers to implement the optimum reconfiguration policy in the manufacturing line. The fluid dynamic system analogy demonstrates a more visual concept of the ideas related to reconfiguration and scheduling in manufacturing systems. Several simulations were performed to show the effects of reconfiguration on manufacturing. A basic simplified mathematical model, based on this analogy, was presented for the capacity and/or functionality of the manufacturing system. The model was used as the basis for a stability analysis, and a quantitative measure of performance, and the results then interpreted in terms of RMS. A quantitative measure of performance, J, can be used to compare dedicated and flexible manufacturing systems to reconfigurable ones. Together with appropriate cost information, this can help a manufacturer select between traditional DML, or FMS, and RMS for a given production situation. The proposed method is also a basis to develop a policy design algorithm for the reconfigurable manufacturing system.

A reconfigurable manufacturing system application, involving the production of two different products with changing demand, was used to illustrate the dynamics of reconfiguration. The simulations clearly show the importance of the reconfiguration delay (T) and gain (K) on the performance of RMS.

REFERENCES

Asl, F.M., and Ulsoy A.G., Analytical Solution of a System of Homogeneous Delay Differential Equations via the Lambert Function , 2000 American Control Conference, Chicago, Illinios.

Birge, J., Duenyas I., Narongwanich W., When Should One Invest in Reconfiguration Capacity? , ERC/RMS Technical Report TR98-23, 1998.

Goldman, S.L., Nagel, R.N., and Preiss K., Agile Competitors and Virtual Organizations: Strategies for Enriching the Customer, Van Nostrand Reinhold, New York, 1995.

Koren, Y. and Ulsoy A.G., 1997, Reconfigurable Manufacturing Systems, ERC/RMS Technical Report 1, University of Michigan, Ann Arbor, Michigan.

Koren, Y., 1997, Open-Architecture Controllers for Machine Tools, ERC/RMS Technical Report 3, University of Michigan, Ann Arbor, Michigan.

Kota, S., 1997, Modular Machine Tools, ERC/RMS Technical Report 4, University of Michigan, Ann Arbor, Michigan.

Kusiak A., Engineering Design: Products, Processes, and Systems, Academic Press, San Diego, CA, 1999.

Mahoney M., High-Mix, Low-Volume Manufacturing, Prentice-Hall, 1997.

Mehrabi M., and A. G. Ulsoy, (eds.), 1997, State-of-the-Art Review of Reconfigurable Manufacturing, ERC/RMS Technical Report 2, University of Michigan, Ann Arbor, Michigan.

Patterson R., Hardt D., and Neal R., 1997, Next-Generation Manufacturing: A Framework for Action, Agility Forum, Leaders for Manufacturing, and Technologies Enabling Agile Manufacturing, Bethlehem, Pennsylvania. National Research Council, Visionary Manufacturing Challenges for 2020, 1998, pp.30-38.