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Bullwhip effect in Integrated Manufacturing and Service Networks

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Abstract - An Integrated Manufacturing and Service Network (IMSN) is a grouping of companies, working together to offer a bundle of products and product-related services, that deliver value to customers over the entire useful life of the product, from purchase to disposal. The success of such an alliance is highly dependent on the seamless integration and interaction of business strategy, operational processes and enterprise systems between constituent companies and their design, manufacturing and sales operations. In this paper, we present system dynamics models to study the behavior of an IMSN and investigate the bullwhip effects that arise within such networks due to mismatches and delays between the manufacturing and service systems within the network. We show that integration and collaboration between the manufacturing and service operations with two-way information flow between them enhances profitability and minimizes the bullwhip effect within repair centers.

Index Terms – Manufacturing, Service Network, Supply Chains, Service Center Design.

I. INTRODUCTION

The increasingly competitive nature of markets, driven by globalization and the maturation of markets in developed countries, has put the customer in the driving seat. Consequentially, customer loyalty has become a key driver of a company's competitiveness and profitability. Hence, in order to retain customers and maintain market share, companies have no choice but to design, manufacture and sell offerings that customers want and demand. Increasingly customers are looking for simple and convenient end-to-end solutions that satisfy its immediate needs and desires, without the need for getting tangled in associated activities and processes that do not directly serve its interests.

The primary characteristic of an IMSN that differentiates it from its competitors is its ability to appreciate and exploit the interaction between the product development, manufacturing and after-sales operations of a product. Constituent companies within the network continually interact and share information and knowledge across all phases of the product development and deployment cycle, namely design, manufacturing, sales and after-sales service. Decisions made during design and manufacturing phases affect the performance and costs during the service phase. On the other hand, provision of good service boosts product sales and the feedback from service operations to design can help produce more reliable products. It is thus important to take a holistic and integrated view of a company's operations incorporating maintenance and serviceability in addition to manufacturability at the design and planning stage in order to be efficient and effective.

In this paper, we attempt to study the benefits of such an approach based on integrating manufacturing and service operations. More specifically, we want to quantify the benefits of information sharing between the design, manufacturing and sales divisions of a manufacturer and its associated service centers. Towards this end we develop cause-effect diagrams and system dynamic models to mimic the operation of an IMSN.

An important consideration in designing an IMSN is the bullwhip effect in the integrated system which can lead to the service system exhibiting oscillatory behavior in resource levels for repair crews, spare parts, etc. We develop system dynamic models for an IMSN and employ it to establish the benefit of:

1. Exploiting feedback from the service centre during product design to improve product serviceability and reliability.
2. Employing sales information in planning future service capacity requirements and reducing bullwhip effect.

Due to the unique nature of issues addressed, our study here on the development of models for IMSNs and analysis of their behavior is a significant contribution to the literature on design of manufacturing-service networks.

II. LITERATURE SURVEY

One can view IMSN from multiple perspectives, namely the evolution in customer preferences, business integration trends, economic development and planning management trends at the level of the product lifecycle, as shown in Figure 1.

In terms of literature tracking the development of IMSNs from the customer perspective, there are lots of white papers and reports from consultants, such as Accenture and McKinsey & Co., on the benefits of selling solutions rather than products [4]. It is now established through various surveys that profit margins in service are much higher than in product sales. For certain types of industrial equipment such as heavy machines and aircraft engines service is an integral part of product sales proposition. In terms of the economic development, from manufacturing to service based economies, there have been studies on the importance of manufacturing in a service economy [3]. Additionally, while the supply chain process integrates all activities from product development to sales of a product, the integration of the service phase,

physically, informationally and organizationally, with the rest of the supply chain is an emerging trend.
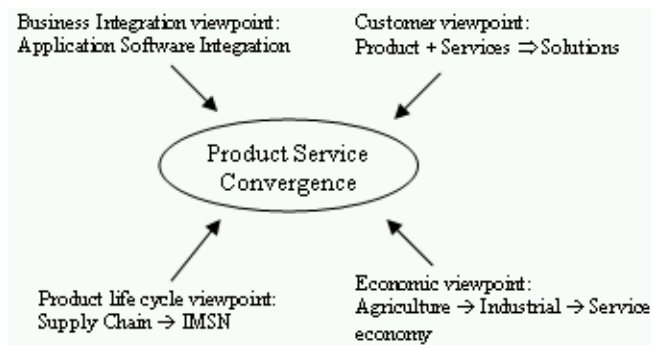

Figure 1: Perspectives on Product Service Convergence

Traditionally, most attention in the Product Lifecycle (PLC) has been given to the direct chain of events i.e. from the design to the customer, but the service and recycling phases are not integrated with other phases in the PLC. In service literature, preventive maintenance [5], the repairman problem [5] and spare parts management have received a lot of attention. Cohen et al. [2] report on a benchmarking study of 14 companies in electronics, computing and communication industries. Cohen et al [1] build a product life-cycle model to study a set of strategic choices facing the manufacturer of durable good as he designs the joint product/service bundle.

Our motivation here is slightly different from the previous literature, since we focus on proving the benefits of collaboration between manufacturers and their service partners, so that each phase in the PLC can benefit and contribute towards the creation of better products or attainment of higher service levels.

III. MODEL DESCRIPTION

A typical IMSN is characterized by interaction between the design, manufacturing, sales and service operations, as shown in Figure 2. We focus on complex products that are economically attractive to maintain and service rather than replace.
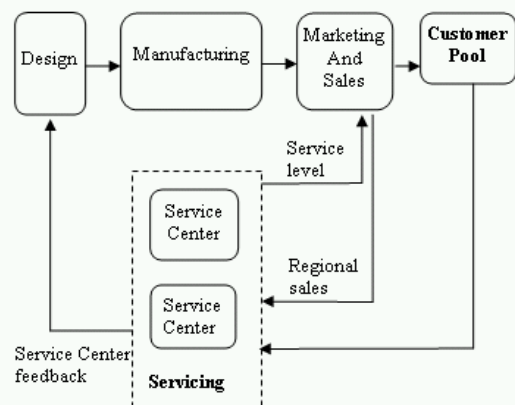

Figure 2: A typical manufacturing-service network

The manufacturer designs the product, produces it and subsequently markets and sells it to a pool of customers. With time and usage the performance of the product

deteriorates and it needs to be serviced at a service center, which typically would employ a variety of resources such as repair crews, disassembly tools, diagnostic equipment, and spare parts. The resources of the service center determine the service levels in terms of the delivery time. The service center capacity is determined by the availability of spare parts and that of skilled repairmen. In this study we assume that the capacity is variable and can be changed with a delay of four months.

It is known from the literature that after sales service quality influences the product sales particularly from the past customers. We incorporate this in our system dynamics model by making service level a variable that influences product sales. Better service level would entice a customer to buy the product, thereby ramping up its sales. Information exchange between the design teams, service centers, manufacturing plants, and marketing and sales can lead to dramatic improvements in the performance of the manufacturing service system, by ensuring proper coordination between all the parties concerned. In particular, future service center resource planning can be enhanced by sharing information on past regional sales, whereas information on current service levels provided by repair centers can help improve the sales forecasts of the marketing department, by adjusting for drops or gains in service levels as we show in the following sections.

IV. MODELING IMSNS

We first present a simple model to show benefits of collaboration between the manufacturing, marketing and after-sales service teams. The model demonstrates that sharing information between manufacturing and service phases can have a huge impact on the performance of the system. In particular, the interaction between the production rates, sales levels, population of deployed goods, repair rates, service levels amongst others is considered in this model, as illustrated in Figure 3.
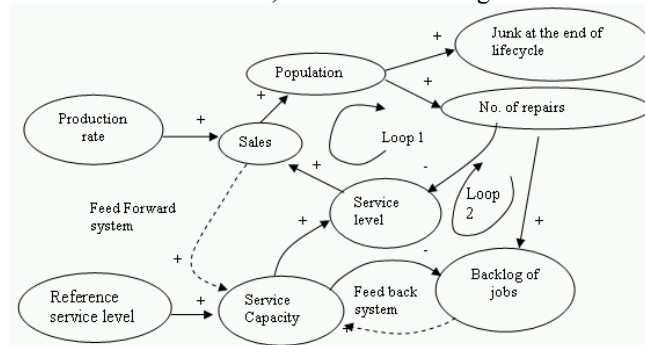

Figure 3: Cause-Effect diagram for Conceptual Model

On the supply side, we assume that goods are produced at a constant rate and they are sold at a rate dependent on the utility function. A higher utility to the customer would result in higher sales, whereas a lower utility would result in lower sales. The sold goods enter the population of deployed equipment while excess goods are inventoried for later sale. As the deployed product is used, over time its performance deteriorates. Eventually when it

fails, it comes in for repairs at a service center. At the service center the product is repaired, within the service capacity limits of the service center, by employing the right mix of manpower, spare parts and repair tools.

As the population of goods sold increases, the number of products coming in for repair also increases. Hence in order to maintain service quality and service times, the capacity of the repair centers need to be increased, or synchronized with the population growth, so that they can handle the higher inflow of goods coming in for repairs. This phenomenon is represented in Loop 1 in Figure 3, wherein it may be noticed that as the population increases, the number of products requiring repair increases, in turn leading to backlog of repair jobs, lower service levels and consequentially lower product sales. This drop in sales needs to be controlled by appropriately controlling the service capacity, which has a direct positive influence on the service levels and an indirect influence on the product sales. To address this problem, we explore two alternative mechanisms, feedback and feedforward, to manage service center capacity as described below, and represented by the dotted lines in the cause-effect diagram in Figure 3.

a. **Feedback system**: The first mechanism is a feedback mechanism wherein performance degradation at the service centers leads to a corrective addition of service capacity that reduces the backlog of repair jobs. This mechanism is represented in Loop 2 in Figure 3. It may be noticed that whenever jobs get accumulated for repair, the service capacity augmentation process is initiated and consequentially new capacity is added to the service center after a fixed lead time, which corresponds to the time required to train repairmen and procure required spares and tools. Such a mechanism is reactive in nature and most service centers typically operate in this fashion when they have no information about product sales. The capacity requisition in our feedback model is based on the following relation:

Capacity ordered on any day = (Rate of arrival of new jobs)*1.1 + (Backlog of jobs) / 5 – Existing Capacity – Capacity in the process of procurement

Similarly, when it is noticed that the service center has excess capacity it is eliminated. In our model we assume that the service center is monitored daily for excess capacity, which is removed based on the following equation:

Amount of capacity freed = Current Capacity - 1.2*(Job arrival rate) - Backlog

b. **Feedforward system**: The second mechanism that may be used to manage service levels is one based on the concept of feedforward. In a feedforward system sales data would be utilized to firstly forecast the population growth of deployed products, secondly to predict the number of future failure events and ultimately to calculate the service capacity requirements to support the expected repair needs of the forecasted population. Hence, taking into account the lead-times for service capacity addition, in a feedforward-based system, we can ensure timely increase

in service capacity such that service deterioration is minimized. Information visibility and collaboration that is pervasive between the manufacturing, sales and service operations of an IMSN is well suited to support a feedforward based control for service capacity management.

In our model, we have assumed the lead time for service capacity addition, to be 120 days and accordingly every 120 days the population growth is forecasted and the expected daily repair events or equivalently the additional required service capacity is determined as follows:

Capacity ordered every 120 days = Population growth in 120 days * Failure rate

Similarly, we assume that excess capacity is removed from the system based on the following relationship:

Amount of capacity freed = Current Capacity - 1.2*(Job arrival rate) – Backlog – Capacity to support expected population growth

The cause-effect diagram for an IMSN, as shown in Figure 3, was developed as a system dynamics model in the IThink software and simulated to observe the long-run behaviour of IMSNs. For our analysis we assumed that the IMSN was in the automobile industry with the following parameters and assumptions.

1. A production rate of 1000 units/day.
2. Car life of 10yrs or 3650 days.
3. Service level being the sole factor influencing sales based on the following relationship.
   Product Sales = (Mean_Service_level - 0.7)*10000/3.
4. *Mean number of failure per day = 0.01*Population*
5. Service capacity acquisition lead-time of 120 days attributable to delays in hiring and training.
6. Product life-cycles 10 years or longer.
7. A single repair job completed in one day if one unit of capacity dedicated to the job.
8. Service level for a particular day defined as the ratio of repairs completed in the day to the total number of incoming repair jobs in the day plus previous backlogs. Since the number of repairs completed is at most equal to the capacity, *Service level = Min (Capacity/Total number of failures, 1).*

Under the above assumptions, the ideal service center capacity is equivalent to the mean number of failures which is one percent of the current population in our model. Our analysis proceeds by a simulation of both the feedback and feedforward strategies outlined earlier.

4.1 Bullwhip effect in Manufacturing Service Networks

An IMSN based on a feedback mechanism responds to the accumulation of jobs by increasing the service center capacity. However since there is an inherent delay in acquiring and deploying service capacity, the service capacity addition is not immediate. Consequentially the service levels continue to decline and jobs continue to accumulate in the interim period. Hence, to rapidly clear the backlog of jobs and to bring the service up to the desired levels, sometimes more capacity than required needs to be added. Thus the reactive feedback system

results in a bull whip effect: a sudden increase in product sales after a lag creates a need for excess service capacity. Because of the leadtimes involved in service capacity addition, the service centers are unable to maintain their service levels and accordingly the sales decline as shown in Figure 4. The fluctuations in service capacity observed in the system (as shown in Figure 4) can be prevented by promoting collaboration between the manufacturing, sales and the service operations of the IMSN.
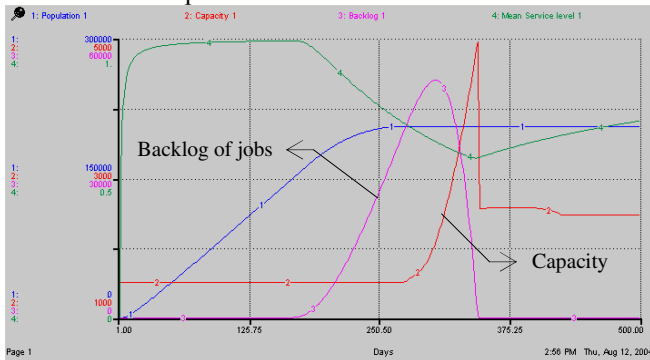

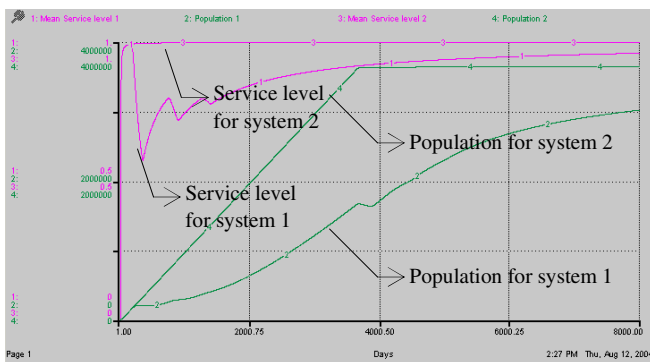Figure 4: Service capacity buildup to clear accumulated jobs

Figure 5: System with Feed-forward and Feedback maintain higher service level than system with only feedback mechanism

In addition the performance of an IMSN based only on feedback was compared to that of an IMSN with both feedback and feedforward mechanisms, as shown in Figure 5. It may be noticed that the feed-forward system is able to maintain very high service levels while the feedback system shows fluctuations. This is because the feed-forward system is better able to forecast service capacity requirements ahead of time and can prepare for it better. On the other hand, an IMSN based on a feedback mechanism shows considerable deviations in the service level over time, which in turn effects the population growth. From Figure 5, it may be noticed that due to consistently high service levels for an IMSN with feedforward, as compared to an IMSN with feedback, the sales of products and consequentially the deployed population for an IMSN with feedforward will be higher over time.

V. MODELING SERVICE CENTERS

From the analysis above, it may be observed that service quality management is greatly enhanced by information sharing and collaboration between the manufacturing and service networks. However, our analysis above was based on a very simplistic black-box representation of a service center based on the assumption that the service center is characterized solely by its capacity and that it utilizes a single resource type.
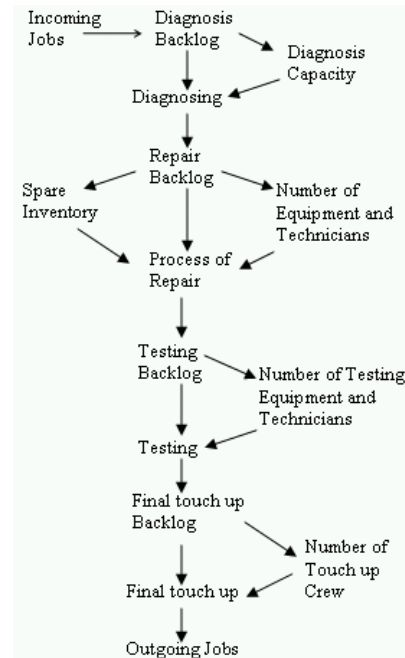

Figure 6: Service Center work flow

A more realistic representation of a service center would model the progression of a repair job through various sequential stages such as diagnosis, repair and testing and would highlight the interaction between the utilization of various resource types such as manpower, tools and spare parts at each stage. In this section, we attempt to develop just such a model for a generic service centre and simulate the operation of the service centre to illustrate the bullwhip effect witnessed in the capacity and resource levels of the service centre. We also establish that information sharing across the various operations of the service centre can mitigate the effect.

For our analysis we consider a generic repair centre, where jobs arrive at the steady rate of 10 jobs per unit of time. Each job is processed through a sequential step of activities beginning with diagnosis and followed by repair, testing and a final touchup as shown in Figure 6. The resources required for the completion of each activity are different. For example, diagnosis requires diagnostic equipment whereas the repair process requires technicians, equipment, and spare parts.

The service center was simulated using a system dynamics framework and the initial value for each of the resources was assumed to be zero. As the job starts arriving the resources are hired to match the demand. It was observed that the variability in resources increases with each successive stage as shown in Figure 7. This is similar to the bullwhip effect observed in the supply chains.Thus we see that resource management is a

challenging problem in service centres and even a small change in the rate of job arrivals can have drastic effects on resource requirements and their levels, which get magnified down the line as well. This further reinforces the importance of information exchange in better managing service networks.
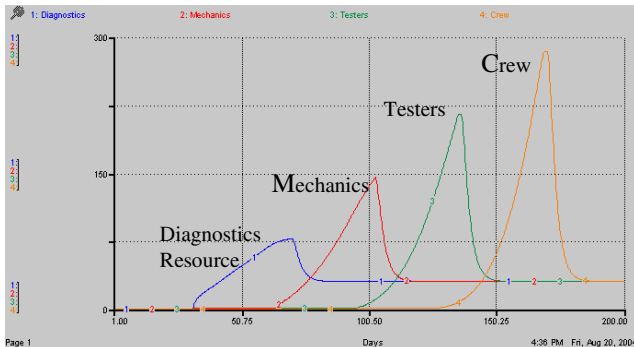

Figure 7: Bullwhip effect in the resources of service center

VI. MODELING IMSNs WITH A SINGLE PRODUCT

The basic model presented in Section 4 is simplistic in its assumption that the consumer's decision to buy a product is based primarily on the quality of the service. However, in reality the purchase decision is influenced by multiple factors such as the price and quality of both the product and the service and the quality and length of the warranty period. In this section we attempt to incorporate these features to build a more realistic model of an IMSN that manufactures and services a single product.

For our analysis we assume that the utility of a product to a consumer is a linear function of product price and quality, service price and quality and the length of the warranty period.

Utility = -Product price + 1000*Product quality - Service price +1000*Service level + Free service contract.

Product price and service price have a negative influence on the utility function since higher prices deter customers from buying the product. Similarly, free service contract periods, better product and service qualities, have a positive influence on the utility as perceived by customers. Furthermore, we also incorporate a reference utility function, similar to the utility described above, which defines a target utility level for the company to aspire towards. In reality this reference utility is equivalent to the utility of the products offered by the competitors. In this manner we are able to account for competitive pressures facing an IMSN. As can be expected, the better the product offered by the IMSN, relative to the competition, higher its sales. Hence, the number of sales that take place in a day is directly proportional to the difference between the reference utility (utility of competitive offerings) and utility of the product offered by the IMSN. If a product service bundle offers superior value the demand for the product will expectedly increase. However increased sales and growth in the product population will over time result in more service demands putting a strain on service levels and quality, requiring some kind of monitoring process to remedy the service

deterioration. The influence diagram for an IMSN manufacturing and servicing a single product under the above operating assumptions is presented in Figure 8.
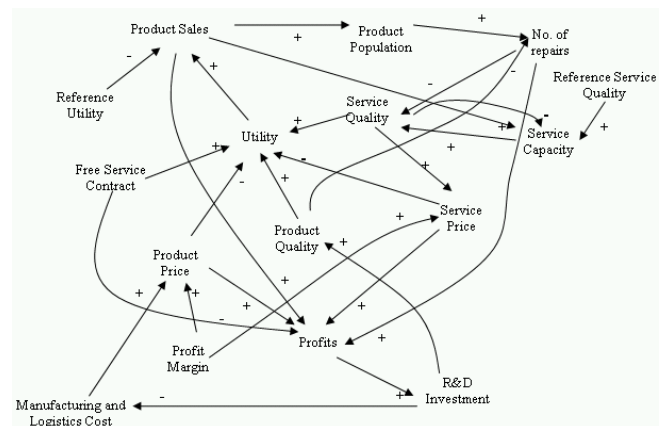

Figure 8: Influence diagram for IMSN with single product

The profits of the IMSN are derived from the sales of both products and services, less the cost of production, service provision and cost of providing free services during warranty. In addition, we assume that a fixed percentage of the profits are continually invested in R&D. These investments bear fruit at a later time in the form of improved product quality, reliability and reduced product prices, in turn stimulating further sales and profits. Concurrently, as the product quality improves, the reliability of the product increases and the number of failure events and consequentially repairs is reduced. In this manner, the concept of design for serviceability is included in our model of an IMSN. However for the sake of simplicity, we have assumed aggregated models for service centres, each of which are geographically distributed. One key differentiating factor in the extended model presented in this section, as compared to our earlier analysis, is the assumption that the product failure rate increases with the age of the product. With an increase in product sales over time the population grows at a higher rate, resulting in greater number of repair jobs. Also, as a product gets old it comes more often for repair. Hence, to predict the load on the service centre we need to *track both product sales and the age of the installed base.*

Additionally, we incorporate the feedforward and feedback mechanisms, explained in the earlier sections, for controlling the interaction between the manufacturing and service sectors and for ensuring that service levels are maintained at the required level. For example, in a feedback based system, if the service level drops below the reference service level, service capacity is added. On the other hand, in a feedforward system, the sales data is employed to forecast and plan for additional capacity requirement.

The model was simulated in IThink to demonstrate that the feed-forward system is better than the feedback system in terms of its ability to improve service levels and the bottom-line for the IMSN. For the simulation study, it was assumed that the lead time for service capacity addition was 120 days and the initial capacity was set to be

adequate to meet all demands occurring in the first 120 days of operations. Based on growth of the population and age of installed base a forecast is made for number of failures per day after 240 days and the required extra capacity is added as appropriate. From the influence diagram it may be noticed that the dynamics within this extended and realistic model are more intricate than the basic model presented in Section 4 (Figure 3), establishing the fact that it is harder to predict the behavior of realistic IMSN models. Our analysis was based on the following parameters and assumptions.

1. One unit of service capacity costs 100 units of money per period.
2. The price charged for service dependent on the service level offered as dictated by the following relationship. *Service Price = Service capacity cost*(1 + service level).*
3. Profit margin of 10% incorporated in the price of products
4. Product quality & Manufacturing cost improves non-linearly for incremental investments in R&D, meaning that the ROI for R& D investments is more than 100%.
5. The probability of a product failing increases over time.
6. The product becomes obsolete in 6 years, in a non-linear manner, as it rapidly becomes outdated in its first few days before being gradually replaced over time.
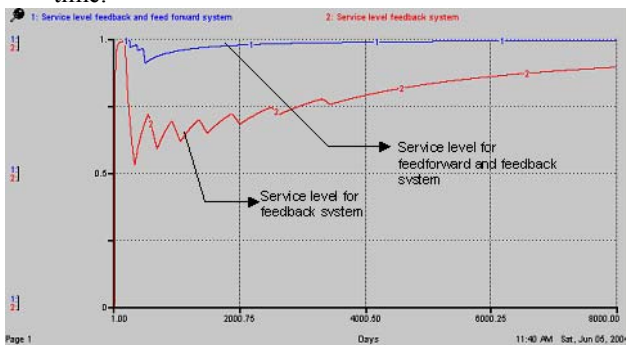

Figure 9: Comparison of service levels for an IMSN with feedback and one with both feedforward and feedback mechanisms

The service levels for IMSNs with only feed-back and with both feed-back and feedforward were simulated and compared as shown in Figure 9. Clearly an IMSN with feedforward and feedback mechanisms is able to provide consistent service levels, inspite of the dynamics involved in the system. It may be observed from Figure 10 that the service capacity growth in an IMSN with a feedforward system is more planned in comparison to an IMSN with just a feedback system. Since one unit of service capacity is needed to complete a single repair job in a day, the service capacity over time in a well synchronized manufacturing service network, such as one with a feedforward system, will trace the number of incoming repairs jobs. However, due to the long lead-times in service capacity acquisition the service capacity increases only in a stepwise manner. It may also be noticed that the excess service capacity added in an IMSN with only

feedback is eventually eliminated as the backlog of service jobs is cleared. The models for IMSNs with both feedback and feedforward were simulated over the entire lifecycle of the product and their profits compared. The profits in an IMSN with both feedback and feedforward mechanisms are 50% higher than the profits for an IMSN with only feedback.
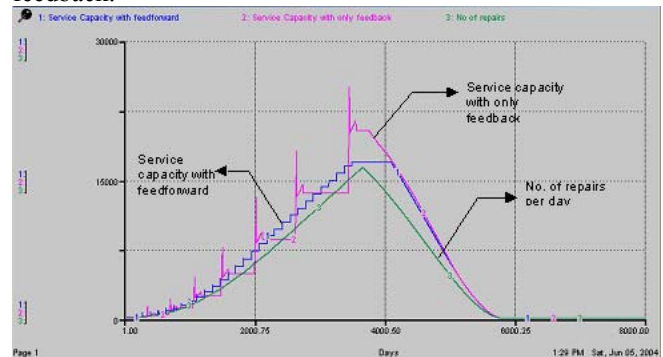

Figure 10: Comparison of service capacity for system with only feedback and system with feedback and feedforward mechanisms

VII. CONCLUSION

In this paper, we have studied the integration of manufacturing and service networks through information sharing and collaboration and highlighted the behavior of such systems. While there are several studies in the form of business cases and white papers on the benefits of such integration, ours is the first systematic study providing a framework for the analysis and design of integrated manufacturing systems and service operations planning in support of strategic manufacturing and sales objectives. We plan to develop queueing network and Petri-net models to further study and develop analytical models for IMSNs.

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