Title: A Network Based Approach for Bottleneck Scheduling in the Process Design of Flow-shop Operations

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Abstract: This project is to develop an approach to the analysis of the bottlenecks in flow-shop operations. The focus is on the identification and elimination of bottlenecks in the flow-shop environment, while considering the balance between the costs and benefits of this bottleneck reduction/flow enhancement analysis. The approach developed in this paper utilizes the out-of-kilter algorithm, minimum-maximum cost, and flow network algorithm to identify the bottlenecks, while maximizing the profit expected from the manufacture of certain products.

A Network Based Approach for Bottleneck Scheduling in the Process Design of Flow-Shop Operations

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PORTLAND STATE UNIVERSITY
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A NETWORK BASED APPROACH FOR BOTTLENECK SCHEDULING IN THE PROCESS DESIGN OF FLOW-SHOP OPERATIONS

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ABSTRACT

The purpose of this study is to develop an approach to analyze the bottlenecks in flow-shop operations. The focus of the study is on the identification and elimination of bottlenecks in a flow-shop environment, while considering the balance between the costs and benefits of this bottleneck reduction/flow enhancement analysis. The approach developed in this paper utilizes the out-of-kilter algorithm, a minimum cost-maximum flow network algorithm, to identify the bottlenecks, while maximizing the profit expected from the manufacture of a certain product. The proposed approach is based on the solution of this network model utilizing the Netsolve software package and implementation of a duality theory based bottleneck analysis procedure, considering the economical and physical aspects of improving the system performance.

1. INTRODUCTION

In today's global marketplace, as competition continues to intensify, markets are getting more segmented, and becoming more demanding. These factors critically impact today's manufacturing environment. They also bring new issues into consideration in the manufacture of products for these global markets. As Kaplan [28, p.96] points out,

> "Today's global competition requires new measures - on quality, inventory, productivity, flexibility, deliverability, and employees - which should be included in the evaluation of a company's manufacturing performance."

In conjunction with Kaplan's statement, Skinner [43, pp:114-116] points out the notion that "a good plant is a low cost plant" is no longer the sole critical issue, since customer driven objectives like short product lead times, quick delivery, reliability, flexibility of production and quality of products are more important objectives for a manufacturer to ensure success. Umble and Srikanth [46, p.36] suggest three approaches that are practiced by today's manufacturers to obtain or maintain an advantage over competitors in their struggle to achieve a competitive edge. These approaches are;

- Produce better quality products
- Offer superior customer service
- Be a low-cost producer.

The manufacturer who is able to improve his or her product quality by assuring the product's conformance to the design standards; increase customer service by shortening lead times and delivering products to the customer on time; and become a low-cost producer, maintains an obvious advantage over the firm's competitors. Consequently, such a manufacturer can often capture additional market share, obtain a higher profit margin per unit, which results in a lower break-even point and increased profits. This, in turn, can lead to opportunities to enhance long term competitiveness through increased investment in research and development, new technology, employee development programs, and productivity and quality improvement activities [46, p.100].

As the requirements for survival in today's manufacturing environments became more demanding, the management of manufacturing operation's has returned to prominence as a key corporate strategic weapon. Today, cutting edge firms employ quantitative methods and computer programs in conjunction with human resource approaches to successfully manage their operations.

Recently, "Optimized Production Technology" (OPT), or the "Theory of Constraints" (TOC) (see [6], [7], [20], [21], [22], [26], [29], [32], [33], [35], [41], [46], [47] among others) has emerged as an alternative manufacturing management philosophy to support manufacturers in their struggle for survival and search for excellence in meeting the expectation's of today's competitive markets. An important aspect of TOC philosophy is the different operational measures that it utilizes in achieving the goal of the manufacturing organization. As a populizer of this philosophy, Goldratt [20, p.260] defines the goal of the manufacturing organization simply as "to make money; both today and in the future." Umble and Srikanth [46, p.29] state the key activities that govern a plant's performance in achieving this goal as;

- The sale of finished products.
- The purchase of raw materials and component parts.
- The transformation of material into finished products.

Based on these three activities, the operational measures of TOC philosophy are defined as [46, p.29];

Throughput	:	The quantity of money generated by the firm through sales over a specified period of time.
Inventory	:	The quantity of money invested in materials that the firm intends to sell.
Operating Expense	:	The quantity of money spent by the firm to convert inventory into throughput over a specified period of time.

The definitions presented above will be used throughout this study. Considering these definitions as the basis, the goal of the manufacturing organization can be restated as "reducing the operating expense and inventory while simultaneously increasing throughput [39, p.188]." As the TOC philosophy defines the goal as "to make money" via maximizing the throughput, manufacturing organizations should focus on the impediments to maximizing throughput. These impediments are usually termed as "bottlenecks," which throttle the capacity of the manufacturing operations [47, p.38].

A bottleneck in the flow of material through a factory resembles the flow of liquid through a pipe, an analogy suggested by Nahmias [38, pp.761-764]. As Figure 1 illustrates, the flow of a liquid through a pipe is the rate at which the liquid can flow through the narrowest portion of the pipe, at D. If the diameter of the pipe at A, B, C, or E is changed, assuming that the change does not decrease the diameter below that at D, there will be no change in the total throughput rate. However, if the diameter of the pipe at D is changed, the total throughput rate will change accordingly.

If the various diameters of the pipe from A through E are considered as the steps or operations in the production process, where the diameters of the pipe represent the respective production rates in the process, then the bottleneck in the process is said to occur at D. This means that any delay at D results in a decrease in the flow of material through the system, but a delay at another step may not result in a delay in the system. Time lost at D is production lost. Until the flow at other stations equals the flow at D, no production is lost in the total throughput of the system, if production decreases at the other stations. The only way to increase throughput is to increase the flow at D, which can be done by either increasing the diameter at D or adding a parallel pipe next to D. In a production setting, this is equivalent to expanding the production capacity of D or adding another machine or workstation like D.

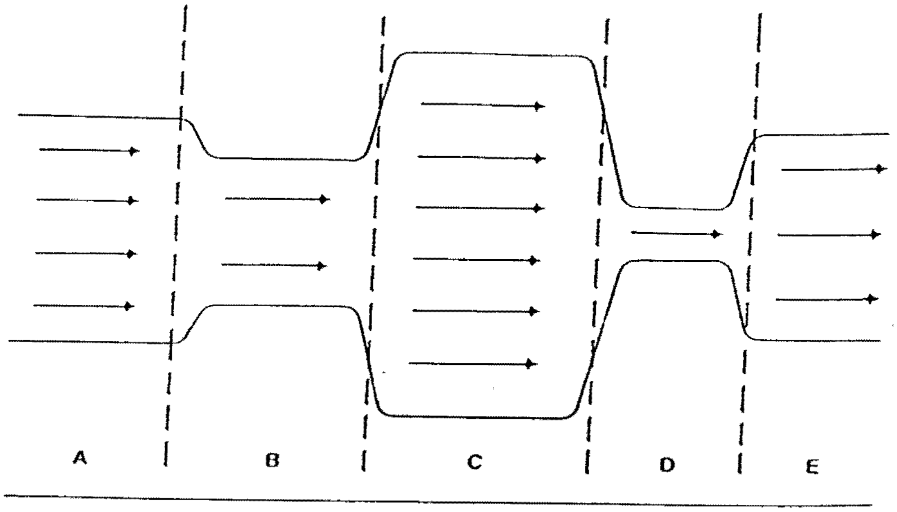


Figure 1. A pipe of varying thicknesses to illustrate Bottlenecks [38, p.761]

Since bottlenecks hold the key to the output of the whole manufacturing system, they should be considered extensively at each stage of the manufacturing operations, including production scheduling and process design phases. Jacobs [26, pp.90-94] discusses the TOC principles, which summarize the role of bottlenecks and constitute the justification for the approaches developed in this study, as follows;

1. *Balance flow, not capacity.* The idea behind this principle is to focus on maximizing the total flow through the system rather than trying to balance work loads. Effective use of imbalance minimizes the likelihood that time is lost at bottlenecks.
2. *The level of utilization of a non-bottleneck is determined not by its own potential, but some other constraint in the system.* In Figure 1, the effect of the capacity at portion D of the pipe, since it determines the flow rate through portions A, B, C, and E, can be easily noted.
3. *Utilization and activation of a resource are not synonymous.* Activating a resource which is not needed does not correspond to intelligent utilization of that resource. In Figure 1, there is no benefit to running C at full capacity while D cannot absorb its output.

4. *An hour lost at a bottleneck is an hour lost for the total system.* If a bottleneck machine is left idle or a breakdown occurs at a bottleneck, the lost time can never be recovered and the production flow will decrease.
5. *An hour saved at a non-bottleneck is a mirage.* Saving time or increasing production at a non-bottleneck location will have no effect on the system production rate. In Figure 1, increasing the diameter of the pipe at A will not increase the flow through the system.
6. *Bottlenecks govern both throughput and inventory in the system.* One purpose of inventory is to keep bottleneck machines busy. Improper planing of Work-In-Process (WIP) inventories can adversely affect product flow.
7. *The transfer batch might not, and many times should not, be equal to the process batch.* The transfer batch is the number of units transported from one work center to another, and the process batch is the size of a production or process run. Because setup costs for processing and transporting are different, batch sizes should be different.
8. *The process batch should be variable, not fixed.* Lot sizing should depend upon the schedule and the operation.
9. *Schedules should be established by looking at all constraints simultaneously. Lead times are the result of a schedule and cannot be predetermined.*

The purpose of this study is to develop an approach to analyze flow shop operations, in a manner consistent with the TOC philosophy. The main focus of the study is on the identification and reduction of bottlenecks in a flow shop environment, while considering the balance between the costs and the benefits of this bottleneck reduction/flow enhancement analysis. In the later parts of this paper, the mathematical model, which constitutes the basis for the approach developed in this study, will be explained. An example case will be described and formulated using the mathematical model presented, followed by the implementation of the bottleneck elimination procedure on the solution provided by Netsolve [12, pp.419-463] software package.

2. LITERATURE SEARCH

In the broadest sense, the approach that is utilized in this study is the implementation of sensitivity analysis on the results provided by a minimum cost maximum flow network algorithm in order to identify and eliminate the bottlenecks, restricting the flow through the system, via acquisition or reallocation of available resources so as to maximize both the throughput and the profitability of the manufacturing organization. In this section, a review of the related literature on the key topics utilized in developing the approaches will be summarized.

2.1. BOTTLENECK SCHEDULING

Although there is extensive literature related to most of the topics involved in this study, such as network theory, and linear programming (see [1], [2], [9], [15], [16], [17], [18], [23], [25], [30], [34], [40] among others), the number of studies regarding the direct application of bottleneck scheduling and utilization of mathematical models or network algorithms in bottleneck scheduling is more limited (see [16], [23], [25], [34], among others). While the bottleneck problem has been well known among operations research analysts, and intuitively recognized among practitioners, it has been popularized lately by the pressure of increased global competition and the rise of a number of advanced manufacturing methods and technologies. Even with this popularization, the underlying modeling concepts are often not fully developed or revealed. As Schragenheim and Ronen [42, p.19] state, the Theory of Constraints (TOC) philosophy, which was promoted in 1970s by Eliyahu Goldratt [20] and titled as Optimized Production Technology (OPT) (see [20], [21], [22], [26], [29], [33], [35] among others), is the first methodology that is based on the bottleneck concept and emphasizes the role of the bottlenecks in the manufacturing operations. The same authors [42, p.20] define the TOC as a "global managerial methodology" which focuses on the system's constraints, their exploitation according to the goal of the organization, and the implications of exploiting these constraints on the rest of the system. As Schragenheim and Ronen [42, p.20] state, the principles of TOC are based on the identification of bottlenecks in the manufacturing process, with the objective of basing the scheduling efforts on these bottlenecks. Recently, Synchronous Manufacturing [41, p.21] emerged as a state-of-the-art manufacturing control system that focuses primarily on the key constraints and control points in the plant (see [7], [41], [42], [46] among others). The objective of this system is to maximize throughput while minimizing inventory and controlling operating expenses [41, p.21]. Under the synchronous manufacturing concept, the objective is to synchronize the manufacturing flow because this methodology states that manufacturing plants cannot be exactly balanced and some resources have more available capacity than others [41, p.22].

In a recent study by Neely and Byrne [39, p.187], the authors state that Materials Requirement Planning (MRP), Just-In-Time (JIT) and TOC are in fact quite complementary. The authors [39, pp.189-190] present an outline framework for their integration. Using computer simulation, the authors [39, pp.190-192] examine different aspects of TOC philosophy and present some preliminary results of their work. Their [39, p.192] findings suggest that taking account of bottleneck resources when scheduling impacts favorably on performance of the manufacturing systems. The authors [39, p.192] state that bottleneck scheduling should be the first step in developing an integrated approach to materials control.

2.2. PRODUCTION PLANNING

In the production planning literature, there are various studies focusing on areas such as process design, machine assignment, and production scheduling via linear programming and/or network models (see [10], [27] among others). However, only limited number of studies consider the details on bottlenecks and their role in the manufacturing operations, beyond those referred to in the previous section. In his classification of machine assignment problems, Elmaghraby [10, pp.245-246] mentions the importance of bottlenecks at the operation level and categorizes the problems in four classes, two of which focus on the bottlenecks and elimination of bottlenecks;

- The optimal assignment of jobs to machines to maximize the minimum efficiency achieved, while each machine can operate on all jobs but with varying degrees of efficiency - as measured, for example, by the machine's productivity per unit time. This is a typical problem in assembly line production where semiskilled labor can be utilized on almost all the operations with varying levels of performance. The productivity of the whole line is the productivity of its weakest link or "bottleneck" operation. Hence, the interest is maximizing the minimum-productivity operation.
- The optimal assignment of jobs to machines that maximizes the total productivity of the machines available, where each machine can operate on all jobs but with varying degrees of efficiency (or productivity). The problem arises in the context of machine shop loading, in the allocation of loads to carriers, etc.

Based on the considered problem type and proposed network approach, it can be noted that the primary concerns of this paper and the classification stated above show similarities, since the main purpose in both approaches is the maximization of the minimum-productivity operation and the allocation of the resources to maximize the capacity of the bottleneck resources. However, another primary concern of the approach presented in this study, the maximization of profitability, is not directly emphasized in the approaches for the problem types presented by Elmaghraby [10, pp.245-246].

Beside the machine assignment models, process selection formulations that are found in the literature also show similarities with the approaches presented in this study. The models described by Johnson and Montgomery [27, pp.115-119] focus on a common type of problem, which consists of fixed production requirements for each of a number of products during a period. In these type of problems, each product may have several alternative options (sources, routings, and processes) by which it can be produced. The unit costs and resources utilized depend on the process selected. In addition, each production resource has a given limited availability in the period, and various products compete for this available capacity according to the particular production processes selected for each product. The problem is defined by the authors [27, pp.115-116] to determine how much of each product is to be made by each process to minimize production costs, subject to constraints imposed by resource limitations and the requirement that the total demand for each product be produced. Although the approach utilized in Montgomery and Johnson's [27, pp.115-116] study shows similarities with the approach presented in this paper (choosing the process sequence for the product which maximizes the output and minimizes the cost), their approach does not consider maximization of throughput, which creates the sole difference between the two approaches.

While this paper focuses primarily on batch and continuous flow-shop operations, the work of Lawrence and Chevalier [30, p.1018] on job-shop type operations strengthens the focus of this study. It provides support for designing the processes based on the bottleneck resources. In their study, the authors [30, p.1018] give a general description of a job-shop operation which explains the "real" job-shop environment, supporting the need for an approach that takes care of the bottleneck resources. Their [30, pp.1019-1021] study considers three main decisions; due-date setting, job release and priority sequencing. Lawrence and Chevalier [30, pp.1019-1021] state that for a successful scheduling of job-shop operations, regulating the amount of work on the shop floor for the bottleneck stations carries primary importance since this action reduces the amount of WIP inventory substantially, without affecting throughput rate of the shop. In addition, they [30, p.1020] indicate that better due-date performance can be achieved over the long run by focusing on efficient system performance and ignoring due-dates when making priority sequencing decisions. Lawrence and Chevalier [30, pp.1018-1021] propose a sequencing policy that maximizes the utilization of the bottleneck machines, and hence, over the long run reduces the backlog of job's waiting to gain entrance onto the factory floor, then allowing the shop to offer shorter due-date lead times. Consequently, Lawrence and Chavalier [30, p.1019] point out the importance and benefit of scheduling the shop floor based on the capacities of the bottleneck resources.

In addition to mathematical models, heuristic models are commonly used in solving flow-shop scheduling problems. In a recent study by Minagawa et al [36], the authors present an approach which utilizes a Generic Algorithm (GA) based heuristic to solve a flow-shop scheduling problem with alternative resources. At each stage of a production line, multiple resources (machines) with different capabilities are arranged. In another study by Cao et al [8], the authors present a heuristic based algorithm for scheduling a set of different tasks to be processed on serial processors that provides an approach towards minimizing the entire makespan and improving productivity.

Sundaram et al [45] present an integrated process planning and scheduling procedure. The same authors state [45, p.296] that process planning and scheduling should be integrated in manufacturing as this action would contribute to reducing production cost immensely. The procedure that they [45] developed seeks not only to minimize the makespan but also balance the loads for machines. Considering bottlenecks in such a development would be a key factor for an organization adopting advanced manufacturing methods.

In a recent study by Agnetis et al [2, p.294], the problem of flow management for a class of flexible manufacturing cells is reviewed. The authors [2, p.294] consider a cell which is deigned for cyclic production of one product. The product is characterized by a sequence of operations of given length and each requiring a set of resources. Therefore, the problem is stated [2, pp.295-296] as the allocation of such resources and scheduling of the operations in order to synchronize the operations and maximize the throughput. The authors [2] present a general model and discuss several cases, corresponding to either polynomial or NP-complete problems.

While there is vast array of production scheduling literature, the references briefly summarized above illustrate the importance of the consideration of bottlenecks. Throughput, quality and economic considerations are highlighted as the key elements of advanced manufacturing system development and design.

2.3. NETWORK MODELS

In this paper, a minimum cost-maximum flow network model is utilized as a basis to identify the bottlenecks in a production flow and to provide targets to implement a bottleneck elimination procedure in order to maximize the throughput and the profitability of the manufacturing system.

Although network models are used extensively in the optimization of telecommunication and transportation flows (see [1], [2], [4], [9], [18], [34], among all), limited number of studies were found in the public literature on production management and process design detailing their use in actual systems. An interesting network algorithm implementation is presented by Ashour and Parker [4]. In their study, the authors [4] present an out-of-kilter algorithm to deal with the machine sequencing problem in which both job precedence and machine non-interference constraints are involved. Their study [4, pp.207-220] illustrates the network model underlying the approach utilized in the first example of this study in detail.

Network models are also utilized in multiple-facility, multiple-product, production scheduling problems. Dorsey et al [9, p.1271] present a study that focuses on this type of problem, to determine an assignment of products to facilities that meets all product demands on a first come, first-served basis, while minimizing the production, inventory and backordering charges during the considered periods. In their study [9, pp.1271-1278], the authors present a linear, mixed integer program formulation for a multiple-facility, multiple-product, production scheduling problem which is then transformed into an all-integer program that is formulated as a minimal-cost network flow.

In addition to single commodity networks, multi-commodity networks, where several items (commodities) share arcs (resources) in a capacitated flow, are also utilized in production planning and distribution problems. Multi-commodity network models can be considered in solving multi-product production scheduling problems. Evans and Martin [11] present two different multi-commodity network formulations; one for maximal flow problems with both upper and lower arc capacities, and the other for capacitated minimal cost trans-shipment problems. In a recent study by Aderohunmu and Aronson [1], the authors present a network aggregation/disaggregation approach for solving a multi-period network model with side constraints. Their [1, p.54] model describes production planning and distribution problem. Instead of solving the original multi-commodity problem, the authors [1, p.62] transform the problem so that a pair of single-commodity network flow problems can be solved.

Ford and Fulkerson [15, p.97] present a simplex computation for an arc-chain formulation of the maximal multi-commodity problem, which can be utilized in designing a manufacturing system where several products should be manufactured using the same resources. The basic network models to be utilized in this study will be discussed in more detail in section 3.

3. MATHEMATICAL MODEL

The problems related to process design and production scheduling show a great variety due to the diverse nature of real world operating environments and the solution techniques utilized in solving these problems. This study focuses on a particular type of problem which is thought to reflect the prominence of controlling bottleneck resources in flow operations and provide a good example for the solution technique proposed in this work.

The process types that are considered in the literature are outlined below referring to a classification by Fogarty et al [13, pp.3-10].

- <u>Flow-Shop</u>:

  Askin and Standridge [5, p.95] define a *flow-shop* operation as the one in which all the products visit the same sequence of workstations. Fogarty et al [13, pp.3-7] classify flow-shop operations as;

  <u>Continuous Flow</u>:

    Production or processing of fluids, powders, basic metals, and other bulk items.

Dedicated Repetitive Flow:

Production of only one product, including product variations(such as color) that require no setup delay in the assembly or manufacturing process.

Batch Flow:

This flow type is functionally the same as the continuous or the repetitive, except that two or more products are manufactured in the same facility, where the manufacturing runs for each product typically last several hours or several days, because of long setup times in the batch flow shop.

Mixed-Model Repetitive:

This type of processes are used to manufacture two or more models. However, the changeover time between models is minimal, and the different models are intermixed on the same line.

- Job-Shop:

Fogarty et al [13, pp.8-9] state that a job-shop process is characterized by the organization of similar equipment by function. As jobs flow from work center to work center, or department to department, a different type of operation is performed in each center or department. Orders may follow similar or different paths through the plant, suggesting one or several dominant flows. This layout is intended to support a manufacturing environment in which there can be a great diversity of flow among products.

- Fixed Site:

The key identifying characteristic of fixed site production is that the materials, tools, and personnel are brought to the location where the product is to be fabricated.

The problem types that are considered in this study focus mainly on flow-shop operations. Since the proposed approach considers the flow of the products through the system as the continuous flow of a liquid through a pipe, the focus is on continuous and batch type flow-shop operations. These are the types of processes considered in the problem that will be presented and analyzed in the later stages of this study.

The approach utilized in the flow-shop problem is based on minimum cost-maximum flow network models. The theory underlying the solution technique proposed for the problem type in consideration will be explained in the following section of the study. The example case problem will be defined in a later section and the solution to the problem will be explained in detail. The main objective of the study is to implement a bottleneck elimination procedure to cost effectively relieve the identified bottlenecks pursuing the optimal maximum profit solution. This objective will be illustrated executing the procedure developed in this study through various scenarios.

3.1. NETWORK FLOW MODEL

The mathematical model utilized in solving the considered problem type is a network flow model. Numerous studies have been reported utilizing network flow algorithms to handle a special class of linear programming problems (see [2], [4], [15], [18], [25], [34] among all). These studies consider problems that can be described as networks whose links carry flow. As Woolsey and Swanson [48, p.100] point out, network algorithms take advantage of their special structure to produce an optimal solution more effectively, with less storage required, and with virtually no round-off error in comparison with general linear programming. In the approach that is utilized in this study, the material flow through the shop floor is assumed to be a continuous flow, like the flow of a liquid through a pipe. This is a valid assumption for continuous flow type manufacturing operations where parts are processed in large numbers.

The stages of the network solution approach developed in this study can be stated as follows;

1. Formulation of the manufacturing system as a capacitated network
2. Solution of the network model using a minimum cost-maximum flow network algorithm
3. Identification of the bottlenecks occurring in the system
4. Elimination of the bottlenecks

These stages will be explained in detail in the following paragraphs.

1. Formulation of the manufacturing system as a network model:

In this study, formulating a manufacturing process as a network model and solving the model using a "minimum cost-maximum flow" algorithm is considered as the method for achieving the goal of manufacturing, defined as "making money" in the TOC philosophy. The TOC philosophy defines its own performance measures for today's competitive environment. The "goal of manufacturing" expressed in terms of the TOC measures is stated as;

Throughput = Revenue generated through sales - Material Cost of goods
Operating Expense = Total Cost of Goods - Material cost of goods
Net Profit = Throughput - Operating Expense

As the "money" earned is the difference between the throughput and the operating expenses, the only way to increase the profit is either to increase the throughput, which is maximizing the quantity of money generated by the firm through sales, or decrease the operating expenses, which is minimizing the quantity of money spent by the firm to convert the raw materials into throughput. This, of course, assumes that output does not increase above the market demand, which is a potential bottleneck. Therefore, the main focus of a manufacturer striving for accomplishing the "goal" of manufacturing should be on the elimination of the impediments preventing the accomplishment of the goal. Bottlenecks, which were discussed in detail in the preceding section of this study, are the major barriers blocking the flow of materials through the manufacturing system, resulting in restricting the throughput of the manufacturing system. Elimination of these bottlenecks considering the balance between the costs and benefits of this action is presumed to open the way to the maximization of throughput, which will maximize the profit as a result.

Thus, the network approach developed in this study focuses on the accomplishment of the "goal" through the maximization of throughput by eliminating the bottlenecks throttling the flow of products through the system.

Minieka [37, p.87] describes a flow through a network as the way of sending objects from one node or point to another by travelling the arcs in their directed paths. For example, the shipment of finished goods from a manufacturer to a distributor, the movement of people from their homes to places of employment, routing of telephone messages through wires, or the movement of products through a production process can all be regarded as flows through networks. Minieka [37, pp.87-90] defines the node from which the objects only depart as the *source*, and the node at which they only arrive as the *sink*. If the number of flow units that can travel across some arc (x,y) is limited, which is usually the case in problem types that are considered in this study, then arc (x,y) is called a *capacitated arc*.

An example network representation of a simple flow-shop operation is illustrated in Figure 2. In this example, each capacitated arc, except for the dummy activity which is included in the model in order to maintain the circulation of flow, represents a machine/operation. In addition to the labels representing the types of machines or operations, the cost, lower production capacity, and the upper production capacity of each machine/operation are illustrated above each arc. The source node is denoted by (s), while the sink node is denoted by (t).

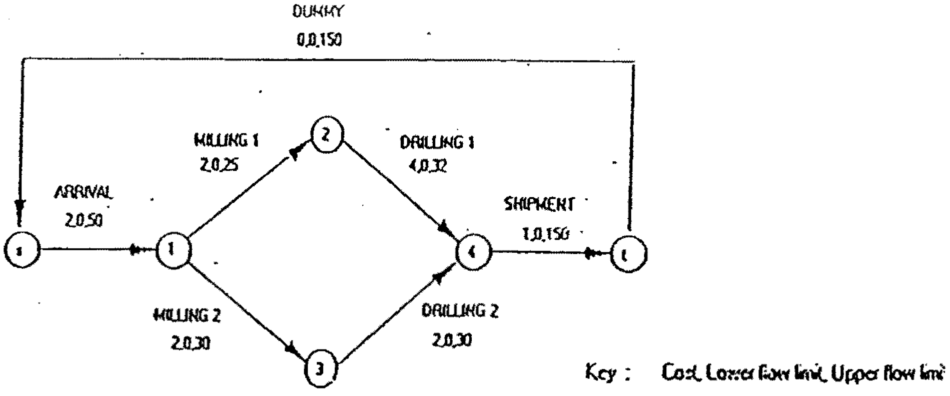


Figure 2. Network representation of a flow-shop operation

In this study, each machine or operation in the manufacturing process of a product will be denoted by a capacitated arc. The maximum capacity of the arc would be the maximum production capacity of the machine or the operation in unit per time period. The minimum capacity of the arc would be the required minimum production rate (which may even be zero) of the machine or operation. The nodes at the start and at the end of each arc will indicate the arrival of the products to that machine or operation to be processed, and the departure of the processed parts from that machine or operation, respectively.

While describing the model utilized in this study, the maximum capacity of arc (x,y) will be denoted by h_{ij} , the minimum capacity of arc (x,y) will be denoted by l_{ij} , and cost or benefit of arc (x,y) will be denoted by C_{ij} or - C_{ij} . Therefore, "costs" will have "positive" signs while "benefits" have negative signs, since the approach maximizes the flow while "minimizing" the cost. In this study, as a result of switching the signs, the algorithm will provide the "maximum profit-maximum flow" solution.

2. Solution of the formulated network model

The second stage of the developed approach is the solution of the formulated network model utilizing a minimum cost-maximum flow network algorithm. The primary objective of the approach used in the case examined is to find the maximum flow from the source node, which is the process or operation releasing the jobs to the shop, to the sink node, which is the last process or operation receiving the jobs from the shop, that minimizes the total cost of production. Since the costs are incorporated as "positive" figures while the benefits are included as "negative" figures in the proposed model, the provided solution will be the "maximum profit-maximum flow" solution. In other words, this is the amount of flow, which maximizes the total revenues from the production of the product, subject to capacity restrictions on the flow in each arc and conservation of flow at each node. Consequently, the standard out-of-kilter algorithm [14, p.162] is utilized as the "minimum cost-maximum flow network" algorithm in the proposed approach. It is assumed that the volume of the product being produced does not exceed the demand. The out-of-kilter algorithm is a very general and efficient algorithm for solving network flow cost problems [48, p.100]. These factors, coupled with its wide availability, constitute the basis for its selection as the solution algorithm for this study.

Ford and Fulkerson [14, p.164] give the following brief explanation of how the out-of-kilter algorithm works;

> The out-of-kilter algorithm operates in such a way as to maintain a circulation in the network while rerouting flows so as to minimize the sum of cost times flow and satisfy capacity restrictions on each arc. This generates an optimal solution to the minimum cost circulation network problem. The theoretical aspects of this process arise from the primal-dual theory of linear programming (complementary slackness).

The theoretical aspects underlying the out-of-kilter algorithm will be summarized in the following paragraphs.

Let;

X_{ij} = Flow from i to j

C_{ij} = Unit cost of flow from i to j

l_{ij} = lower bound on flow in arc i,j

h_{ij} = upper bound on flow in arc i,j

The linear programming formulation of the minimum cost-maximum flow network model is stated as follows [37, p.105];

$$Min\ Z - \sum_{i}\sum_{j} C_{ij}\, X_{ij} \qquad (1)$$

$$\sum_{k} X_{ki} - \sum_{k} X_{ik} - 0 \qquad (2)$$

$$X_{ij} \geq l_{ij} \qquad (3)$$

$$X_{ij} \leq h_{ij} \qquad (4)$$

where, constraint (2) represents conservation of flow, indicating that whatever comes into a node must exit; constraint (3) represents a lower bound on flow; and constraint (4) represents an upper bound on flow.

The dual to the above formulation results in the following model [37, p.111]; Let

v_{ij} = Dual variable for lower bound constraint which indicates the value of unit change on the right hand side of the lower bound constraint

u_{ij} = Dual variable for upper bound constraint which indicates the value of unit change on the right hand side of the upper bound constraint

g_i = Value of a unit of flow at node i

g_j = Value of a unit of flow at node j

$$Max\ G - \sum_i \sum_j l_{ij}\, v_{ij} - \sum_i \sum_j h_{ij}\, u_{ij} \qquad (5)$$

subject to;

$$g_j - g_i + v_{ij} - u_{ij} - C_{ij} \qquad (6)$$

g_i , g_j are unrestricted in sign

$v_{ij}, u_{ij} \geq 0$

Because constraint (2) is an equality constraint, g_i and g_j variables are unrestricted in sign. v_{ij} and u_{ij} are dual variables for constraints (3) and (4). Since constraint (4) is a $\leq$ constraint in a minimization problem, it must be reversed to be put into standard form to express the dual.

Duality theory states that if a constraint is not binding, that is, its resources are not fully consumed, its dual variable will be zero. For any given X_{ij} , the lower and upper bounds can not be simultaneously binding. Therefore in an optimal solution to the dual at most only one of the variables u_{ij} or v_{ij} should be greater than zero. As the g_i and g_j variables are unrestricted in sign, and the conservation of flow constraints in the primal (2) are assumed to be satisfied at all times, dual variables g_i and g_j can be formulated in a unique fashion.

If constraint (6) is considered again;

$$g_j - g_i + v_{ij} - u_{ij} - C_{ij} \qquad (7)$$

or

$$v_{ij} - u_{ij} \leq C_{ij} - g_j + g_i \qquad (8)$$

If g_i and g_j are interpreted as the value or price of a unit of flow at nodes i and j respectively [48, p.102], and C_{ij} is the cost of flow from i to j, then a $\overline{C_{ij}}$ is defined as;

$$\overline{C_{ij}} - C_{ij} + g_i - g_j \qquad (9)$$

where the economic interpretation of $\overline{C_{ij}}$ can be made as the cost of moving from node i to node j (being processed at ij) plus the value of flow at node i minus the value of flow at node j.

X_{ij} may either be basic ($X_{ij} > 0$) or non basic ($X_{ij} - 0$) .

If X_{ij} is a basic variable, then due to complementary slackness, equation (8) must hold with equality;

$$v_{ij} - u_{ij} = C_{ij} - g_j + g_i$$

$$v_{ij} - u_{ij} = \overline{C_{ij}} \qquad (10)$$

Consequently; if X_{ij} is a basic variable and;

$\overline{C_{ij}} > 0$ it implies that; $v_{ij} > 0$ and $u_{ij} = 0$ and $X_{ij} = l_{ij}$

$\overline{C_{ij}} < 0$ it implies that; $u_{ij} > 0$ and $v_{ij} = 0$ and $X_{ij} = h_{ij}$

$\overline{C_{ij}} = 0$ it implies that; $v_{ij} = u_{ij} = 0$ and $l_{ij} \le X_{ij} \le h_{ij}$

If X_{ij} is a non-basic variable ($X_{ij} = 0$), the implication is that $l_{ij} = 0$, otherwise $X_{ij} = 0$ would not be feasible. This would guarantee that $u_{ij} = 0$. Thus, for a non-basic variable;

$$v_{ij} \le \overline{C_{ij}} \qquad (11)$$

If $\overline{C_{ij}} < 0$ then the non-negativity constraint on v_{ij} is violated

If $\overline{C_{ij}} = 0$ then $v_{ij} = 0$, which implies $l_{ij} \le X_{ij} \le h_{ij}$

If $\overline{C_{ij}} > 0$ then; $v_{ij} = 0$ or $v_{ij} > 0$

If $v_{ij} > 0$ then $X_{ij} = l_{ij}$ as was the case for the basic variable

If $v_{ij} = 0$ then $X_{ij} \ge l_{ij}$ but this assumes that $X_{ij} > 0$, which violates the assumption that X_{ij} is not a basic variable. As a result; $X_{ij} = l_{ij}$

Consequently, if X_{ij} is a non-basic variable and;

$\overline{C_{ij}} > 0$ then $X_{ij} = l_{ij}$

$\overline{C_{ij}} < 0$ then $X_{ij} = h_{ij}$

$\overline{C_{ij}} = 0$ then $l_{ij} \leq X_{ij} \leq h_{ij}$

If one of these conditions are violated, then the branch is said to be "out-of-kilter." The out of kilter algorithm makes changes in the solutions and/or the g_i values in an attempt to bring a branch into kilter. A more detailed discussion of out-of-kilter algorithm may be found in references [12], [14], [17], [37], [48].

3. Identification of the bottlenecks

As this study focuses on the elimination of the bottlenecks in the system, identification of the bottlenecks from the network solution provided by the out-of-kilter algorithm is an important issue. From the definition of bottlenecks it follows that bottlenecks would occur in the system where the resources are fully consumed. In other words, the value of the flow at a bottleneck resource should be equal to the upper capacity limit of that resource. As a result, the bottlenecks occurring in the system can be easily identified by detecting the arcs (machines or operations) with flow values equal to their upper capacity limits.

The capacities and flow values of the arcs (machines or operations) are provided in the first part of the Netsolve [12, pp.420-463] solution output. Considering the Netsolve output, the criteria for identifying the bottleneck and non-bottleneck resources is stated below.

Assuming;

UPPER = Upper capacity limit of the process

FLOW = Current amount of material flow through the process

If, UPPER - FLOW = 0 then the resource is a BOTTLENECK
If, UPPER - FLOW > 0 then the resource is a NON-BOTTLENECK

4. Elimination of the bottlenecks

The elimination of bottlenecks, a primary objective of this study is to be undertaken in a manner to maximize the throughput, which is defined in the TOC philosophy as "the quantity of money generated by the firm through sales over a specified period of time." Throughout this study, the term throughput will be used referring to the definition made by the TOC philosophy.

The solution provided by the utilization of out-of-kilter algorithm is supposed to give the "minimum cost-maximum flow" solution to the problem. However, in the network model that is developed in this study, the revenues from the shipment of each product are used as "negative costs" on the final arcs of the network, while the cost of production on each operation/machine is incorporated with "positive" figures. Thus, in the proposed approach, the absolute value of the "minimum cost-maximum flow" solution provided by the out-of-kilter algorithm is, in fact, the "maximum profit-maximum flow" solution of the network formulation. Under these circumstances, maximum throughput for the manufacturing system is achieved. However, the proposed approach states that this "maximum profit-maximum flow" solution can be improved by increasing the capacities of the bottleneck resources as long as the cost of this improvement is justified by the expected benefits from this operation.

The performance of the system can be improved in two ways;

- Utilization of External Resources
- Utilization of Internal Resources

There are numerous external resources which can be utilized in order to improve the system performance. Purchasing an extra machine to increase the capacity of the bottleneck resource; hiring another operator; or subcontracting the production of the products, which would otherwise be manufactured using the bottleneck resources, to another contractor can be specified among the external resources which can be utilized to improve the system performance via increasing the capacity of the bottleneck resources. The cost justification of the external resource utilization should be done carefully, since these are long term investments including various considerations, such as the training of the work force for running the new machines; reorganization of the manufacturing system; and dependency to the contractor for timeliness of due dates for the required products.

The second method for the improvement of system performance is the utilization of internal resources. Internal resource utilization can be performed by shifting or reallocating the available and flexible non-bottleneck resources' capacities to the bottleneck resources. This reallocation can be done in the form of assigning the non-bottleneck machine operators, after getting the required level of training, to the bottleneck machines in order to utilize this available labor capacity in transferring the processed material; speeding up the set-up operations; running the machine when the operator is not available; or effective handling of breakdown situations. Another way to improve internal resource utilization is assigning another machine which has the capability of performing the operation to process the parts which should be processed by the bottleneck machine.

In the proposed approach, utilization of internal resources, in terms of shifting or allocating the capacities of the available and flexible resources to the bottleneck resources, is given priority against the utilization of external resources like purchasing another machine or subcontracting the production. Generating a more flexible work force by training the employees to become multi-skilled work force and building up the team spirit among the employees are considered as some of the benefits of this internal resource utilization, in addition to the improvement of system performance. Utilizing the internal resources effectively will strengthen the commitment of the manufacturing organization to today's cutting edge concepts such as utilizing self directed teams, emphasizing teamwork, creating multi skilled labor, and becoming a flexible manufacturer.

There are two main concerns in the system performance improvement process. The first one is the identification and selection of the resources which should be improved and the determination of which resources, in terms of external and internal resource alternatives, should be utilized for relieving the bottlenecks. The second primary concern is the cost justification of the available alternatives for performance improvement. Therefore, the cost of improvement should be less than or, at least, equal to the anticipated benefit of utilizing either an external or an internal resource alternative.

In conjunction with the information presented above, a detailed explanation of the network based solution approach proposed in this study is given in the rest of this section.

1) Identify the bottleneck resources;

The first step in the process is the identification of the bottleneck resources throttling the flow of material through the system. Bottleneck resources are the ones which consume all their available capacity. Regarding the solution output provided by the Netsolve package, the bottleneck resources are the ones whose upper capacity levels and the flow levels are equal to each other. In other words, a bottleneck resource can be identified according to the value of the equation;

$$\mathbf{FLOAT_{ij} = UPPER_{ij} - FLOW_{ij}}$$

If $\mathbf{FLOAT_{ij} = 0}$ then the resource on arc ij is a **BOTTLENECK**

where;

$\mathbf{UPPER_{ij}}$ = Upper capacity limit of the resource on arc ij

$\mathbf{FLOW_{ij}}$ = Amount of flow passing through the arc ij

2) Identify the non-bottleneck resources;

The non-bottleneck resources are those which are not consumed totally. These are the resources whose flow levels are less than their upper capacity limits. From the information provided by the Netsolve output, these resources can be identified according to the value of the equation;

$$\mathbf{FLOAT_{ij} = UPPER_{ij} - FLOW_{ij}}$$

If $\mathbf{FLOAT_{ij} > 0}$ then the resource on arc ij is a **NON-BOTTLENECK**

where;

$\mathbf{UPPER_{ij}}$ = Upper capacity limit of the resource on arc ij

$\mathbf{FLOW_{ij}}$ = Amount of flow passing through the arc ij

The magnitude of the difference between the upper capacity limit of the non-bottleneck resource and the current amount of flow passing through the resource indicates how close that non-bottleneck resource is to become a bottleneck.

3) Determine the allowable capacity increase amounts for the bottleneck resources;

At this step of the solution approach, the maximum amount of increase that is allowed to be made in the capacity of the bottleneck resources while relieving the bottleneck resources is determined. Since each maximum profit-maximum flow solution is valid for certain limits of the arc capacities and costs, improvement of these bottlenecks beyond the maximum allowable increase limits will change the solution basis. Consequently, the first intention is maximizing the throughput while preserving the maximum profit solution.

There are two different situations encountered while determining the maximum amount of increase that can be made in the capacity of the bottleneck resources.

(i) The first type of bottlenecks are the ones which do not have any other alternatives in the flow-shop that can perform the tasks which have to be performed by these bottleneck resources. These type of bottlenecks can be described as the operations or machines which are unique in the system. For example, in a flow shop where there is only one milling machine, with an upper capacity lower than the other machines and operations, and there are no other machines that can perform its tasks, the maximum amount of products that will be produced will be equal to the upper capacity limit of the milling machine. These bottlenecks, due to their criticality for the system performance, can be addressed as the **primary bottlenecks.** The upper capacity limits of these bottlenecks are equal to the maximum amount of flow passing through the system which is definitely equal to the amount of flow passing through these bottleneck resources. The allowable increase amount that can be added to the upper capacity limits of these bottlenecks can be determined according to the rule;

Allowable Increase Amount

$$\min(\mathit{FLOAT}_{ij}) \qquad \mathit{for} \ \forall \ \mathit{FLOAT}_{ij} > 0$$

where;

$\mathbf{FLOAT_{ij} = UPPER_{ij} - FLOW_{ij}}$

and;

$\mathbf{UPPER_{ij}}$ = Upper capacity limit of the resource on arc ij

$\mathbf{FLOW_{ij}}$ = Amount of flow passing through the arc ij

(ii) The second type of bottlenecks are the ones which have identical machines in the system that can perform the same tasks that these bottlenecks are performing. The only difference between these bottleneck machines and their identicals is their lower cost of production, which causes these machines to be preferred against their identicals. In this study these bottlenecks will be addressed as **secondary bottlenecks**. For example, there may be a lathe and a numerical control machine in a flow-shop with identical capacities. The tasks that have to be performed on the lathe can easily be performed on the NC machine. However, the cost of production on the NC machine is definitely higher than the lathe. Consequently, the lathe will be preferred against the NC machine and utilized fully till its all of its capacity is consumed. If the total cost of increasing the capacity of lathe is less than the total benefits of this capacity improvement, the capacity of the lathe can be increased. The allowable amount that can be added to the capacity of this type of a bottleneck resource can be determined according to the rule;

Allowable Increase Amount

$$\min(FLOAT_{ij}) \qquad for \quad \forall \, FLOAT_{ij} > 0$$

where;

$\mathbf{FLOAT_{ij} = UPPER_{ij} - FLOW_{ij}}$

and;

$UPPER_{ij}$ = Upper capacity limit of the resource on arc ij

$FLOW_{ij}$ = Amount of flow passing through the arc ij

4) Identify the non-bottleneck resources which can be reallocated;

The presence of non-bottleneck resources does not guarantee that these resources can be utilized for relieving the bottleneck resources. First of all, these non-bottleneck resources should have the availability and flexibility for being shifted to the bottleneck resource. This stage needs a thorough analysis of the flexibility of the non-bottleneck resources in order to decide whether they can either be shifted to or utilized instead of the bottleneck resources. The economic aspects of these actions will be considered in the later stages of this study.

5) Determine the allowable capacity amounts which can be shifted for the non-bottleneck resources;

Non-bottleneck resources have lower and upper capacity limits which limit their range of variation. If a non-bottleneck resource is not basic, this means that it does not take part in the production at all and it has no contribution to the throughput. Therefore, all of its capacity is available for being shifted and utilized in order to relieve the bottleneck resource, if it is physically and economically appropriate. If a non-bottleneck resource is "basic," which means that it takes part in the manufacturing of the product but it is not consumed totally, than the capacity which is not utilized in the production process can be reallocated so that it can be utilized in an other resource in order to contribute to the throughput. This reallocation can be performed if and only if its economical and physical feasibility is justified.

There might be cases where certain amount of capacity is needed in order to improve the process. For example, shifting five units from a non-bottleneck may be required in order to increase the capacity of the bottleneck resource's capacity by one unit. The non-bottleneck resource may be the best alternative economically but it may not be appropriate for reallocation due to its limited allowable capacity. Under these circumstances, determining the amount of available capacity becomes an important issue. Therefore, this step was thought to be a required stage in the bottleneck elimination procedure and was included.

For the non-bottleneck resources, the allowable amount of capacities which can be shifted to the bottleneck resources can be determined according to the rule;

Allowable Decrease

$$u_{ij} - X_{ij}$$

where;

X_{ij} = Amount of flow passing through the arc ij

u_{ij} = Upper capacity limit of the resource on the arc ij

6) *Identify the external resource utilization alternatives which can be adopted in order to relieve the bottlenecks;*

In addition to the non-bottleneck resources, there might be other alternatives for improving the system performance such as purchasing an additional machine or subcontracting the part of the bottleneck operation to another manufacturer. These options should also be considered according to their economical and physical feasibility in order to be utilized in the process improvement stage. The determination of economical and physical feasibility of these external resources will be explained in the later stages of this study.

7) *Determine the additional cost of performance improvement via relieving the bottlenecks, and anticipated benefit of these actions for each appropriate alternative;*

Regarding the internal resource utilization alternatives, which include the shifting of the available capacity amounts of the non-bottleneck resources to the bottleneck resources, the cost of shifting the available capacity to the bottleneck resources is to be determined. Various costs should be considered during this process. Some of these costs might be cost of required training for the transferred employee; additional salary incentive for the reallocated employee; the cost of set-up time reduction activities; the cost of required modification to the machines for running another operation in place of the bottleneck resources.

For the external resource utilization alternatives, numerous sources of cost should be considered. Since the external resource alternatives differ from each other extensively, for each alternative special attention should be paid for identifying the sources of cost. For example, for a machine acquisition alternative, allocation of the cost of the machine; the cost of hiring and/or training the operator; the cost of designing the manufacturing system including the new resource should be considered. However, for an alternative such as subcontracting the production to another manufacturer, considerations become different. For such an alternative, one might consider the allocation of transportation costs; the cost of possible late deliveries; and costs incurred in meeting the product specifications should be among the considerations. A standard engineering economic analysis should be undertaken in each case.

For both of these alternative types, the total of system improvement costs, which will be called as "total improvement costs" (TIC) throughout this study, should be less than or at least equal to the total anticipated benefits from the capacity increase in the bottleneck resource, which will be referredaws "total improvement benefits" (TIB) in this study.

Standard accounting and finance methods are utilized while calculating the "total improvement cost" (TIC). TIC can be calculated per unit or as the total cost for improvement. For both of the approaches, the methodology is the same. While determining the TIC per unit, the total amount of money spent for the total amount of capacity increase, including all the costs such as training and purchasing costs, and divided to the increased capacity of the improved resource. In the approach utilized in this study, the TIC is calculated as the total cost of total capacity increase. Other methods can be utilized as long as the TIB is also determined in same units.

The total improvement benefit of relieving a bottleneck resource can be determined by using the "shadow price" for that bottleneck resource. The shadow price, which is illustrated as the "reduced cost" with a reversed sign in the Netsolve output, is the value of increasing the current upper capacity of the bottleneck resource by one unit. For example a value of (-25.00) for a bottleneck resource in the reduced cost column stands for an increase of ($25.00) in the total profit, for each unit of capacity added to the upper capacity limit of that bottleneck resource.

In order to determine the "total improvement benefits," one must multiply the additional contribution to the profit made by increasing the upper capacity of the bottleneck by the total number of increases made in the upper capacity of the same bottleneck resource. In other words, total improvement benefits for a bottleneck resource is determined by multiplying the absolute value of the reduced cost of that bottleneck by the total number of increase made in the upper capacity of that bottleneck.

Assuming;

TIB = Total benefit expected from the improvement of the bottleneck resource

TIC = Total cost of improving the bottleneck resource

$\overline{C_{ij}}$ = Reduced cost of the bottleneck resource indicated by arc ij

u'_{ij} = Increased upper capacity level of the bottleneck resource

X_{ij} = Amount of flow passing through the arc ij

$$TIB - | \overline{C_{ij}} | * (u'_{ij} - X_{ij})$$

If $TIC > TIB$ then eliminate the alternative

If $TIC \leq TIB$ then select the alternative for consideration

8) *Determine which resources to be utilized in order to improve the process due to the economic feasibility and availability/flexibility considerations of the alternatives;*

At this step, the alternative whose utilization will provide the most benefit to the system will be determined. First consideration in this determination process is the economic feasibility of the utilization of the alternative, while the second consideration is the availability of the resource to be acquired or reallocated. The alternative which has the required availability and provides the most benefit should be selected as the alternative to be utilized. Therefore, the alternative which satisfies the condition; $\max(TIB - TIC)$ where $TIB - TIC \geq 0$ and has the availability to be acquired or shifted is eligible for selection in order to improve the bottleneck resource.

9) *If the allowable decrease and increase limits for the non-bottleneck and bottleneck resources respectively are reached and there are no other available resources to be utilized, the solution is optimal without additional resources.*

10) *If the allowable decrease and increase limits for the non-bottleneck and bottleneck resources respectively are not reached and there are no other available resources to be utilized, cannot be improved any further without outside resources.*

11) *If the allowable decrease and increase limits for the non-bottleneck and bottleneck resources respectively are reached and there are still available resources to be utilized for the improvement of the system, or improvement is required to meet the demand, then these resources should be utilized considering the economic feasibility condition. This action results in the changing of the basis for the solution. A new solution is reached with different basis and solution. Consequently, the*

improvement process can be repeated for these new basis values starting from the first step.

In the following parts of this study, an example problem will be presented and solved utilizing the proposed network approach. The results will be discussed following the implementation of the procedures explained above.

4. EXAMPLE PROBLEM

The example problem utilized in this section to illustrate the network approach to a flow-shop operation is developed based on an example presented by Hesse and Woolsey [24, p.233]. Initially, a description of the problem will be given and then the proposed network approach will be implemented using the data provided by the example.

4.1. DESCRIPTION OF THE EXAMPLE PROBLEM

Hydraulic Specialties Company (HSC) produces precision hydraulic components for the aircraft industry. Higher quality and lower cost have been made possible through the creative development of efficient utilization of advanced manufacturing techniques. Complete units from raw materials to final fluid testing account for 70% of the company's sales. The 30% balance of production is in components such as servo valves which are used in aircraft controls and other sophisticated components.

The more precise the production process, the higher the cost for quality machines and operators. The servo valve requires very precise machining, and tolerances must be held to within 0.00002 inch. This type of work can only be done on the newer machines by the most capable and skilled operators.

HSC has some extra time available on its machines and wants to make the best possible use of it. HSC's processes are designed as a batch type flow-shop system. As a result, machines do not run multiple-products at the same time but process a "batch" of a single-product until a given order is completed. HSC wants to increase its servo valve production while maintaining the balance between the costs incurred in increasing the production and the benefits of this action. Given the figures in Table 1, the problem is to determine if HSC can increase its throughput and maximize the profit.

4.2. ASSUMPTIONS MADE FOR SOLVING THE EXAMPLE

1) This approach does assume that the servo valves produced can be sold, which means that there is demand for this product.

2) In the proposed approach, utilization of internal resources, in terms of shifting or allocating the capacities of the available and flexible resources to the bottleneck resources, is given priority against the utilization of external resources like purchasing another machine or subcontracting the production. Generating a more flexible work force via training the employees as multi-skilled work force and building up the team spirit among the employees are considered as some of the additional benefits of this internal resource utilization approach, in addition to the improvement of system performance. In this example, purchasing new machines and subcontracting the production to other manufacturers in order to increase the capacities of the bottleneck resources will not be considered as options. The non-bottleneck resources will be considered for utilization in relieving the bottlenecks in the system.

3) For the example, only the labor hour capacities of the non-bottleneck resources are assumed to be available for shifting. None of the machines/operations are assumed to be capable of performing the processes of the others, which means that each machine/operation has unique specifications and cannot be utilized instead of others. In this example the cost of the additional capacity is determined as;

For a non-basic non-bottleneck; by multiplying 25 times the operator cost of the shifted resource with the total amount of the capacity shifted.

For a basic non-bottleneck; by multiplying 35 times the operator cost of the shifted resource with the total amount of the capacity shifted.

(This assumption takes care of the training cost of the operator being shifted.)

4) For this example it is assumed that shifting all of the unassigned labor hours

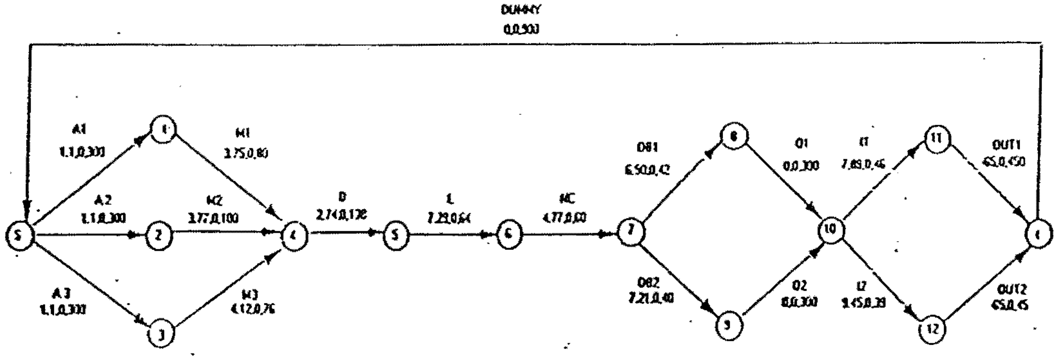
from a non-bottleneck resource to a bottleneck resource increases the upper capacity of the bottleneck resource as much as the allowable increase limit of that bottleneck resource.

Table 1. Data for servo valve production [24, p.233].

		Available Capacity (unit)	Total Production Cost ($/unit)	Time Required (hrs/unit)	Uncommitted Time (hrs)	Machine Cost ($/unit)	Operator cost ($/unit)
Mill	1	80	3.75	0.325	26	2.65	1.1
	2	100	3.77	0.300	30	2.67	1.1
	3	76	4.12	0.340	26	2.82	1.3
Drill		138	2.74	0.216	30	1.92	0.82
Lathe		64	7.29	0.465	30	5.72	1.57
Numerical Control		60	4.77	0.333	20	3.63	1.14
Deburring	1	42	6.90	0.620	26	4.96	2.21
	2	40	7.21	0.650	26	5.17	2.04
Inspection	1	46	7.88	0.650	30	5.67	2.21
	2	39	9.45	0.670	26	6.90	2.55
Raw Material Cost		$1.10	-	-	-	-	-
Selling Price		$65.00	-	-	-	-	-

4.3. SOLUTION OF THE PROBLEM

For the solution to the problem described above, the stages of the proposed approach will be utilized. The first step of the approach is the network formulation of the described manufacturing operations. The network formulation for servo valve production is illustrated in Figure 3.



A1, A2, A3 : Arrival of raw material to Milling operations 1, 2, and 3
M1, M2, M3 : Milling operation on machines 1, 2, and 3
D : Drilling operation
L : Lathe operation
NC : Numerical Control operation
DB1, DB2 : Deburring operation on machines 1 and 2
Q1, Q2 : Queues of Deburring 1 and 2
I1, I2 : Inspection 1 and 2
OUT1, OUT2 : Shipment of the products
DUMMY : Dummy activity to maintain the conservation of flow in the network
LB : Lower bound on allowable arc flow
UP : Upper bound on allowable arc flow

Key: Cost, LB, UB

Figure 3. Network representation of servo valve production

The second step is the solution of the network flow representation of the problem via the out-of-kilter algorithm. For this study, the Netsolve Interactive Software Package for Network Analysis [12, pp.420-463] was employed in order to solve this network model as a minimum cost-maximum flow problem. The solution provided by Netsolve is illustrated in Table 2.

The output provided by the Netsolve package includes information about the selected arcs (operations/machines) as they provide the "minimum cost-maximum flow" solution to the system, which is interpreted as the "maximum profit" solution in the proposed approach since costs and benefits of the products are included in the proposed model with opposite signs.

Table 2. Netsolve output for the servo valve example.

```
MINIMUM COST FLOW PROBLEM:   MINIMUM COST IS    -1806.64

ARC                 FROM        TO          LOWER       FLOW     UPPER     COST
---                 ----        --          -----       ----     -----     ----
ARRIVAL 1           S           1           0.00        60.00    300.00    1.10
QUEUE 1             8           10          0.00        42.00    300.00    0.00
QUEUE 2             9           10          0.00        18.00    300.00    0.00
INSPECTION 1        10          11          0.00        46.00     46.00    7.88
INSPECTION 2        10          12          0.00        14.00     39.00    9.45
MILLING 1           1           4           0.00        60.00     80.00    3.75
DRILLING            4           5           0.00        60.00    138.00    2.74
LATHE               5           6           0.00        60.00     64.00    7.29
NC                  6           7           0.00        60.00     60.00    4.77
DB 1                7           8           0.00        42.00     42.00    6.90
DB 2                7           9           0.00        18.00     40.00    7.21
DUMMY               T           S           0.00        60.00    900.00    0.00
OUT 1               11          T           0.00        46.00    450.00    -65.00
OUT 2               12          T           0.00        14.00    450.00    -65.00


SENSITIVITY ANALYSIS FOR EDGE COSTS

   NODE              DUAL
   ----              ----
   1                  1.10
   10                55.55
   11                65.00
   12                65.00
   2                  1.10
   3                  1.10
   4                  4.85
   5                  7.59
   6                 14.88
   7                 48.34
   8                 55.55
   9                 55.55
   S                  0.00
   T                  0.00

                                 EDGE        REDUCED                       COST RANGE
ARC              FROM     TO     STATE       COST          LOWER           CURRENT          UPPER
---              ----     --     -----       -------       -----           -------          -----
ARRIVAL 1        1        4      BASIC        0.00     -999999.00            3.75            3.77
INSPECTION 1     10       11     UPPER       -1.57     -999999.00            7.88            9.45
INSPECTION 2     10       12     BASIC        0.00           7.88            9.45           38.14
OUT 1            11       T      BASIC        0.00     -999999.00          -65.00          -63.43
OUT 2            12       T      BASIC        0.00         -66.57          -65.00          -36.31
MILLING 2        2        4      LOWER        0.02           3.75            3.77       999999.00
MILLING 3        3        4      LOWER        0.37           3.75            4.12       999999.00
DRILLING         4        5      BASIC        0.00     -999999.00            2.74           31.43
LATHE            5        6      BASIC        0.00     -999999.00            7.29           35.98
NUM.CONTROL      6        7      UPPER      -28.69     -999999.00            4.77           33.46
DEBURRING 1      7        8      UPPER       -0.31     -999999.00            6.90            7.21
DEBURRING 2      7        9      BASIC        0.00           6.90            7.21           35.90
QUEUE 1          8        10     BASIC        0.00     -999999.00            0.00            0.31
QUEUE 2          9        10     BASIC        0.00          -0.31            0.00           28.69
ARRIVAL 1        S        1      BASIC        0.00     -999999.00            1.10            1.12
ARRIVAL 2        S        2      BASIC        0.00           1.08            1.10       999999.00
ARRIVAL 3        S        3      BASIC        0.00           0.73            1.10       999999.00
DUMMY            T        S      BASIC        0.00     -999999.00            0.00           28.69
```

Consequently, the minimum cost solution which was found as (-$1806.64) for the servo valves can, in fact, be interpreted as the maximum profit of ($1806.64), which is the total profit expected from the sales of servo valves.

In addition to the minimum cost (or maximum profit) solution, the values of the flow through the arcs are presented in the output provided by Netsolve. In the sensitivity analysis part of the solution output, the marginal values for variables g_i and g_j are presented in the dual column. In the second part of the output including the sensitivity analysis section, the reduced costs of the activities (production), the lower ranges for the costs of the arcs (production), the current arc (production) costs, and the upper cost range values for the arcs (production) are illustrated.

Thus, the "maximum profit" solution is obtained. At this point the procedure which was explained in the former paragraphs will be utilized in order to improve the system performance further, if it is possible. The first step of the procedure is the identification of the bottleneck resources throttling the flow of material through the system. Regarding the solution output provided by the Netsolve package, bottleneck resources can be identified utilizing the equation;

$$\mathbf{FLOAT_{ij} = UPPER_{ij} - FLOW_{ij}}$$

If $\mathbf{FLOAT_{ij}} = 0$ then the resource on arc ij is a **BOTTLENECK**

where;

$\mathbf{UPPER_{ij}}$ = Upper capacity limit of the resource on arc ij

$\mathbf{FLOW_{ij}}$ = Amount of flow passing through the arc ij

Regarding the Netsolve output presented in Table 2, the Numerical Control (NC), Inspection 1, and Deburring 1 operations are identified as the bottleneck resources, as they satisfy the equation stated above. Netsolve lists these activities as having an edge state of UPPER.

Second step in the process is the identification of the non-bottleneck resources. These are the resources whose flow levels are less than their upper capacity limits. From the information provided by the Netsolve output, these resources can be identified as the ones which satisfy the inequality;

If $\mathbf{FLOAT}_{ij} > 0$ then the resource on arc ij is a **NON-BOTTLENECK**

Mill 1, Mill 2, Mill 3, Drill, Lathe, Inspection 2, and Deburring 2 operations are identified as the non-bottleneck resources.

At the third step of the solution approach, the maximum amount of increase that is allowed to be made in the capacity of the bottleneck resources while relieving the bottleneck resources will be determined.

The NC machine conforms the (i) type of a bottleneck since the current amount of flow passing through this resource, the upper capacity limit for this resource, and the maximum amount of flow passing through the system are equal to each other. Therefore, NC machine can be addressed as a primary bottleneck. Consequently, the allowable increase amount for this bottleneck is calculated according to the rule;

Allowable Increase Amount

$$\min(\mathit{FLOAT}_{ij}) \qquad \mathit{for} \ \forall\, \mathit{FLOAT}_{ij} > 0$$

where;

$\mathbf{FLOAT}_{ij} = \mathbf{UPPER}_{ij} - \mathbf{FLOW}_{ij}$

and;

$\mathbf{UPPER}_{ij}$ = Upper capacity limit of the resource on arc ij

$\mathbf{FLOW}_{ij}$ = Amount of flow passing through the arc ij

The allowable increase amount for the NC machine is determined as;

(64 - 60) = 4 units.

The Inspection 1 and Deburring 1 operations meet the conditions for the (ii) type of a bottleneck resource, since the current amount of flow passing through these resources are equal to the upper capacity limits of these resource while the maximum amount of flow passing through the system is greater then both of these values. Therefore, the Inspection 1 and Deburring 1 operations can be addressed as secondary bottlenecks. Consequently, the allowable increase amount for these bottlenecks are calculated according to the rule;

Allowable Increase Amount

$$\min \left(FLOAT_{ij} \right) \qquad \text{for} \ \forall \ FLOAT_{ij} > 0$$

where;

$FLOAT_{ij} = UPPER_{ij} - FLOW_{ij}$

and;

$UPPER_{ij}$ = Upper capacity limit of the resource on arc ij

$FLOW_{ij}$ = Amount of flow passing through the arc ij

The allowable increase amount for the Inspection 1 and Deburring 1 operations are determined as;

For Inspection 1 (60 - 46) = 14 units.

For Deburring 1 (60 - 42) = 18 units.

As a result, the allowable increase amount for the bottlenecks of this manufacturing system is determined as;

min(4, 14, 18) = 4 units.

At the fourth step of the procedure, available non-bottleneck resources will be identified. Recall it was assumed that the only available resources for shifting are the labor hours of the operators, which are expressed in product units in this example. for this example, it was assumed that shifting a non-bottleneck's allowable capacity would relieve the bottleneck resource. However, the situation may differ from case to case. For example, shifting ten units from a non-bottleneck may be required for increase the capacity of the bottleneck resource's capacity by one unit. Under these circumstances, determining the amount of available capacity becomes an important issue.

For the non-bottleneck resources, the allowable amount of capacities which can be shifted to the bottleneck resources was stated to be determined according to the rule;

<u>Allowable Decrease</u>

$$u_{ij} - X_{ij}$$

where;

X_{ij} = Amount of flow passing through the arc ij

u_{ij} = Upper capacity limit of the resource on the arc ij

According to this rule, the allowable decrease amounts for the capacities of the non-bottleneck resources are determined as;

	Allowable Decrease
Mill 1 ;	20 units
Mill 2 ;	100 units
Mill 3 ;	76 units
Drill ;	78 units
Lathe ;	4 units
Deburring 2 ;	22 units
Inspection 2 ;	25 units

In this example, only one internal resource utilization alternative is considered and that is the reallocation of the labor capacity. TIBs for the bottleneck resources can be determined utilizing the formulas stated below.

Assuming;

TIB = Total benefit expected from the improvement of the bottleneck resource

$\overline{C_{ij}}$ = Reduced cost of the bottleneck resource indicated by arc ij

u'_{ij} = Increased upper capacity level of the bottleneck resource

X_{MAX} = Amount of flow passing through the arc ij

$$TIB - | \overline{C_{ij}} | * (u'_{ij} - X_{ij})$$

For NC; the allowable increase amount is 4 units, therefore;

$$TIB - | -28.69 | * (4)$$

$$TIB - \$114.76$$

For Inspection 1; the allowable increase amount is 14 units, therefore;

$$TIB - | -1.57 | * (14)$$

$$TIB - \$21.98$$

For Deburring 1; the allowable increase amount is 18 units, therefore;

$$TIB - | -0.31 | * (18)$$

$$TIB - \$5.58$$

At this step, the TICs for improving the system performance can be determined considering the assumptions made for this problem.

Assuming;

TIC = Total cost of improving the bottleneck resource

the calculations for each bottleneck resource is illustrated below.

For relieving the NC operation which needs 4 more capacity units;

Non-bottleneck Resource:	Allowable Decrease:	TIC
Mill 1	20 units	(35*1.1)*4 = 154
Mill 2	100 units	(25*1.1)*4 = 110
Mill 3	76 units	(25*1.3)*4 = 130
Drill	78 units	(35*0.82)*4=114.8
Lathe	4 units	(35*1.57)*4=219.8
Deburring 2	22 units	(35*2.04)*4=285.6
Inspection 2	25 units	(35*2.55)*4=357

$$TIB - \$114.76$$

For relieving the Inspection 1 operation which needs 14 more capacity units;

Non-bottleneck Resource:	Allowable Decrease:	*TIC*
Mill 1	20 units	(35*1.1)*14 = 539
Mill 2	100 units	(25*1.1)*14 = 385
Mill 3	76 units	(25*1.3)*14 = 455
Drill	78 units	(35*0.82)*14 = 401.8
Lathe	4 units	(35*1.57)*14 = 769.3
Deburring 2	22 units	(35*2.04)*14 = 999.6
Inspection 2	25 units	(35*2.55)*14 = 1249.5

TIB - $21.98

For relieving the Deburring 1 operation which needs 18 more capacity units;

Non-bottleneck Resource:	Allowable Decrease:	*TIC*
Mill 1	20 units	(35*1.1)*18 = 693
Mill 2	100 units	(25*1.1)*18 = 495
Mill 3	76 units	(25*1.3)*18 = 585
Drill	78 units	(35*0.82)*18 = 516.6
Lathe	4 units	(35*1.57)*18 = 989.1
Deburring 2	22 units	(35*2.04)*18 = 1285.2
Inspection 2	25 units	(35*2.55)*18 = 1606.5

TIB - $5.58

Consequently, the alternatives which satisfy both the economic feasibility and the availability conditions can be determined referring to the rule;

If $TIC > TIB$ then eliminate the alternative

If $TIC \leq TIB$ then select the alternative for consideration

As a result of this analysis, only one alternative is found to satisfy the required conditions. Therefore, the only resource allocation that can be performed in this process is the reallocation of resources from Mill 2 operation to the NC operation since;

$$110 < 114.76$$

When this reallocation is performed and capacity of the NC operation is increased to 64 units while the production cost per unit is increased to;

$$(110/64) + 4.77 = \$6.49$$

a better solution with a higher total profit value compared to the first solution is obtained.

According to this new solution the total profit is ($1811.32) which is a higher value than the ($1806.64) of the first solution. Meanwhile the maximum flow through the system is also improved; increasing from 60 units to 64 units.

The allowable decrease and increase limits for both the non-bottleneck and bottleneck resources are not reached respectively. Although there are other available resources to be utilized, these alternatives could not meet the economic feasibility conditions. As a result, under these assumptions this solution is the optimal solution and no further improvements can be made to the system.

In the last section of the study, the proposed approach and the results from the implementation will be discussed. Suggestions for the future research will be made.

5. SUMMARY

The objective of this study has been to develop an approach to analyze the bottlenecks in flow-shop operations. The proposed approach focuses on the identification and reduction of bottlenecks in a flow-shop environment, while considering the balance between the costs and the benefits of this bottleneck reduction/flow enhancement analysis.

The proposed approach maximizes both the profitability and the throughput of the manufacturing organization. This objective is defined in the TOC philosophy as "the goal of manufacturing organizations," which is stated [20, p.260] as "to make money; both today and in the future." This statement may seem too "out-of-date" for today's markets, where issues like quality, lead time performance, flexibility, reliability, and on-time delivery are considered as more important objectives for the manufacturer. However, when the TOC definition is viewed from a broader perspective, it is realized that the goal of "making money both today and in the future" can only be achieved by meeting the required levels of quality, lead time performance, flexibility, and so forth. Consequently, these key success factors, required from today's manufacturer, can be considered as the building blocks of the main goal, which is "making money; both today and in the future."

The TOC philosophy uses throughput, as the measure of performance in a manufacturing system. Therefore, at the operational level, the goal of the manufacturing organization can be achieved through increasing the throughput while decreasing the operational expenses. Thus, eliminating the impediments of throughput maximization becomes a very important issue in achieving this goal. These impediments, which restrict the capacity of the manufacturing operations, are termed as bottlenecks. Identification and elimination of these bottlenecks, considering the economic balance between the costs and benefits of this operation, improves the system performance, increasing both the throughput and the total profit of the manufacturing organization.

The approach developed in this paper utilizes the out-of-kilter algorithm, a minimum cost-maximum flow network algorithm, to identify the bottlenecks, while maximizing the profit expected from the manufacture of a certain product. The costs of producing a unit on each arc is incorporated into the model as a "positive" figure, while the income from the product is incorporated as a "negative" number. The routine, by minimizing the profit, which is negative in sign, in fact, maximizes the total profit of the production.

The Netsolve [24] software package was utilized in solving the minimum cost-maximum flow algorithm. Netsolve gives the required information for performing the bottleneck elimination analysis. The benefits expected from the improvement of the system were determined using the shadow prices for the bottlenecks in the system. Since these bottleneck resources throttle the flow through the system, increasing their capacities until further capacity improvements would be economically and/or physically infeasible, improves the system performance, increasing the net profit and the total capacity of production.

The proposed approach is applicable in flow-shop type operations, in these type of operations all the products visit the same sequence of processes. It was assumed that for the run of any given batch only one type of product is manufactured and the amount of products in each batch is large enough to assume the flow of materials is continuous. However, the proposed approach can be modified for manufacturing operations where two or more different products are manufactured utilizing the same resources. In these type of operations, the same bottleneck identification and elimination procedure can be practiced utilizing a computer code which can solve the multi-commodity network flow problems.

Another extension of the proposed approach might be considering the assembly type of production operations, where numerous products are assembled together at different stages to produce a final product. Future research can be done in utilizing a decomposition approach in order to solve assembly-node type of problems. In a decomposition based approach, each line, where the sub-assemblies are produced/purchased, can be considered as a separate minimum cost-maximum flow network model. Since the number of sub-assemblies at each assembly node should equal to the required units in the bill of materials, the maximum capacity that can be produced in the assembly system equals the capacity of the sub-assembly line with the minimum capacity. The bottleneck identification and elimination procedure can be integrated with this approach in order to improve the performance of the assembly system.

In addition to network based models, other quantitative techniques can be utilized in obtaining the maximum profit solution with the maximum amount of flow through the system. Parametric programming can be utilized in determining the initial optimal process design, followed by the bottleneck identification and elimination procedure utilized in the proposed approach.

Consequently, the bottleneck identification and elimination procedure developed in this study can be utilized integrating it with other solution techniques and procedures. An analysis of the manufacturing system in order to maximize its profits before starting the production will have extreme importance in the process design stage, especially, for today's highly demanding and competitive markets. As a result, the proposed approach is believed to provide a powerful tool for process improvement while maintaining the high profit levels.