Sequencing and Capacity Planning in Integrated Supply Chains

N. R. Srinivasa Raghavan* N. Viswanadham†

Abstract

In this paper, we present the combined sequencing and rough cut capacity planning problem in integrated supply chain networks. Our approach is different from traditional approaches to rough cut capacity planning, in the sense that we extend the planning problem to the entire supply chain rather than the manufacturing factory floor in isolation. We model the sequencing and planning problem as a constrained non-linear programming problem and present a solution to the same using Lagrangian relaxation. Feasible schedules are obtained by using greedy heuristics. Approximate bounds on the duality gaps are also obtained. Interesting insights into the physics of integrated capacity planning in supply chains are presented.

1 Introduction

One of the toughest challenges the manufacturing enterprises face in today's dynamic, highly competitive marketplace is achieving and maintaining customer satisfaction. Customers are more demanding than ever; insisting on low cost deliveries and customized, highly reliable service tailored to their ever changing demands both in magnitude and variety.

In this paper, we consider the supply chain network (SCN) as an interconnection of facilities such as suppliers, manufacturers, distribution, logistics etc. Each

*Department of Computer Science and Automation, Indian Institute of Science, Bangalore – 560 012, India. email: raghavan@csa.iisc.ernet.in

†Department of Mechanical and Production Engineering, National University of Singapore, Singapore – 119260. email: mpenv@nus.edu.sg

of these facilities itself could be a large dynamical system consisting of several subprocesses and facilities such as machines, trucks, etc. Effective management of the supply chain is essential for meeting customers' needs, retaining their loyalty, and for profitability of all the stakeholders of the supply chain. Conversely, a less-than-optimally functioning supply chain can undermine customer satisfaction and loyalty, thus cutting off avenues for profitable growth.

The critical functions of supply chain management are managing the information and material flows. The problem of materials planning in manufacturing facilities has been considered by several researchers, but only at the firm level, i.e., the sequence of planning procedures beginning from aggregate plans and culminating in the MRP, are done for *each* manufacturing facility. This approach clearly ignores the interfaces and logistics activities between any two facilities, and thus leads to frequent changes in the MRP.

We take a comprehensive view of the supply chain process and address the issue of materials planning in extended enterprises, consisting of suppliers, manufacturers, distribution, etc. Our contribution is in terms of formulating an optimal sequencing and allocation problem for all the facilities that are part of the supply chain process. We use Lagrangian Relaxation approach to this problem. This paper is organized as follows. In section 2, we present the capacity planning problem for supply chains along with the traditional view points. A brief literature review is done too. The methodology used is motivated with a simple illustration. In section 3, we formulate the problem of rough cut capacity planning using Lagrangian Relaxation and briefly give the results to an example. We conclude in the next section by highlighting the major contributions of this paper and giving directions for future research.

2 Capacity planning and sequencing in supply chain networks

At the heart of most organizations' efforts to streamline business processes is the concept of information integration. Modern Enterprise Resource Planning (ERP) solutions, like SAP, BAAN, Oracle, Syteline etc., are designed to accomplish this and provide organizations with a system for planning, controlling and monitoring an organization's business processes. ERP solutions achieve high levels of integration by utilizing a standard mechanism for communications, developing a common understanding of what the shared data represents and establishing a set of rules for accessing data. It is worth noting that in typical ERP implementations, it is mostly one organization with all its SBU's that goes in for one such. Whereas in the case of supply chains where typically there are hundreds of vendors, with scores of manufacturing plants and several layers of distribution, it is not uncommon to find many kinds of ERP solutions being implemented with each member of the supply chain. Thus any capacity planning system for the supply chain must take into account this feature. Such solutions must not only manage and integrate information from a wide variety of systems, but also provide powerful decision-making capabilities.

2.1 Traditional Capacity Planning

In traditional materials planning, we encounter the requirements of a single manufacturing firm, or at best, the collection of all the strategic business units of this firm. The problem of planning in a manufacturing system usually begins with the determination of forecasts and firm orders, for all the goods produced by the company. The work force and production levels required to satisfy the customer demand are obtained from aggregate planning algorithms. Then the master schedule is generated after disaggregation into product families and items. The master schedule, known as the MPS, gives periodic requirements for all the end items. The requirements are then checked against existing production capacities in the plant. This is known as rough cut capacity planning, usually done in iterative manner [15].

The most commonly used planning solutions for complex manufacturing systems are MRP-II/ERP. MRP-II solutions use the BOM explosion, and include three stages of resource requirements planning, rough cut capacity planning and capacity requirements planning. The last examines the actual capacity required by the production plan. For a comprehensive survey on the methods in each of these, refer [10].

The planning problem is usually solved under deterministic settings, using assignment type of linear or non-linear programming problems. See for e.g. [13, 2]. Some stochastic constrained models are also available in [1, 8]. These papers essentially deal with the resource allocation problem for the manufacturing system, given the period-wise demand requirements, the bill of materials structure, the inventory control policy and available levels of various resources of the system. The rough cut capacity planning is done usually, using heuristics and rules of thumb. There are graphical and simulation based approaches to rough cut planning too, for e.g. see [12, 11].

Another approach for planning using the Theory of Constraints (TOC) has been evolved by [4], which has the ability to consider a broad range of constraints and relationships. It explicitly recognizes capacity limitations and uses a heuristic procedure to find an operating schedule. A key insight of TOC is that only a few work centers within the factory control the output of the entire factory for each product line. Managing these capacity constraining resources (CCRs) or bottlenecks optimizes the output of the factory. Knowledge of the plant's CCRs also provides guidance for future plant investment. Consistent with this approach are the flow rate planning methods discussed in [9].

2.2 Integrated planning and sequencing: The physics

Traditional rough cut capacity planning is fraught with disadvantages like:

- It treats each facility in isolation leading to shortages of needed sub-assemblies at some stages and excess inventories of needless components at other stages of the supply chain.
- Works on the myth that 'factories produce well only under pressure', which leads to overloading of the facility towards the end of the planning periods.
- Due to erratic order flows and strong boundaries separating the members of the SCN, there is frequent re-sequencing and reallocation of orders at various facilities, leading to large WIP and long lead times.

We need to re-define several terms like capacity, integrated materials plan, etc., for the supply chain. By capacity of the supply chain, we mean the maximum achievable throughput rate of any facility. Also, at each facility the capacity may mean the processing hours that are free during the planning period, the number of trucks available, the number of alternative suppliers available, etc. In this paper, for the purpose of rough cut capacity planning, we no more consider the material requirements of a manufacturing unit in isolation. We rather redefine what we call as the Supply Chain Master Materials Schedule (SCMMS) for the entire supply chain as a whole. This is the aggregated material requirements for all the manufacturing plants put together, plus the aggregated distribution requirements for the SCN and the aggregated procurement plan for the SCN. This nett amount is what we consider for the purpose of rough cut capacity planning for the SCN. See Figure 1 for the proposed integrated capacity planning model for the entire supply chain. Such an approach, we feel will yield better results in terms of improved utilization at all facilities, as also promptly meeting customer due dates. The focus of our

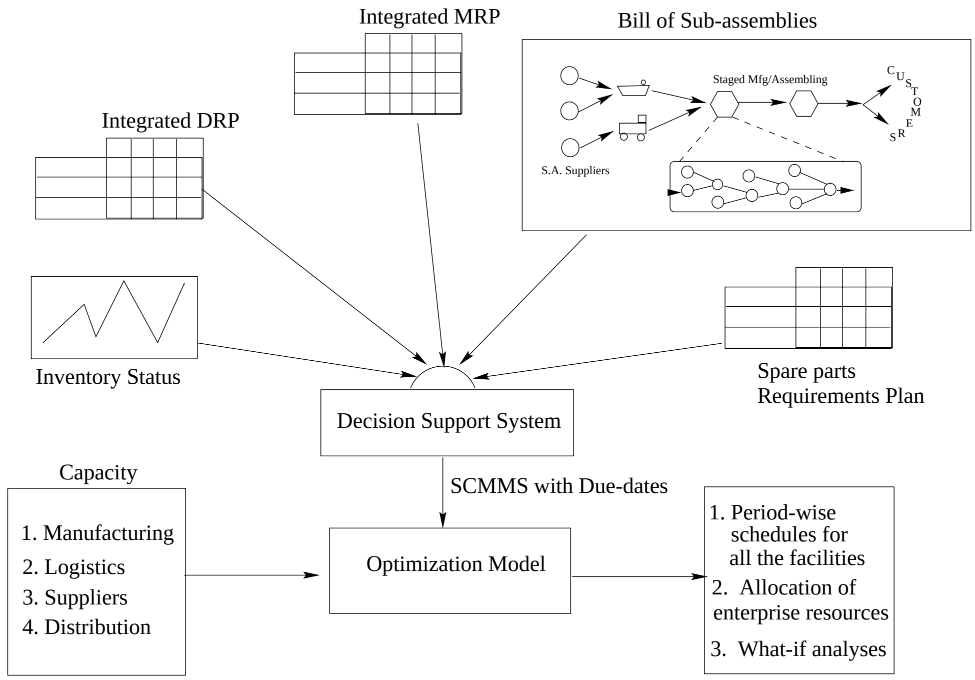

Figure 1: Capacity planning for the integrated supply chain

paper is to develop an heuristic optimization model based on Lagrangian Relaxation approach, to do the combined sequencing and rough cut capacity planning for supply chain networks.

2.3 An illustration

We assume that the aggregated SCMMS consists of requirements in terms of 'units' for any of the following: The sum of actual and Forecasted orders for various end products of the SCN, planned inventory changes made at various facilities, inter facility needs (for e.g. a down stream facility is fed by an upstream one periodically), R & D needs (for e.g. materials needed for prototyping etc.), spare parts and service requirements and intermediate product sales. From this list, it is clear that there are several types of orders flowing through the supply chain, each with its own due dates, product routings, priorities and processing requirements. We preserve the precedence structure by posing them as constraints in the model. Set ups, priorities, processing times are all assumed to be pre-specified.

Order processing consists of any value adding activity done at a facility, like: manufacturing, assembling, packaging, transportation etc. We call the order rout-

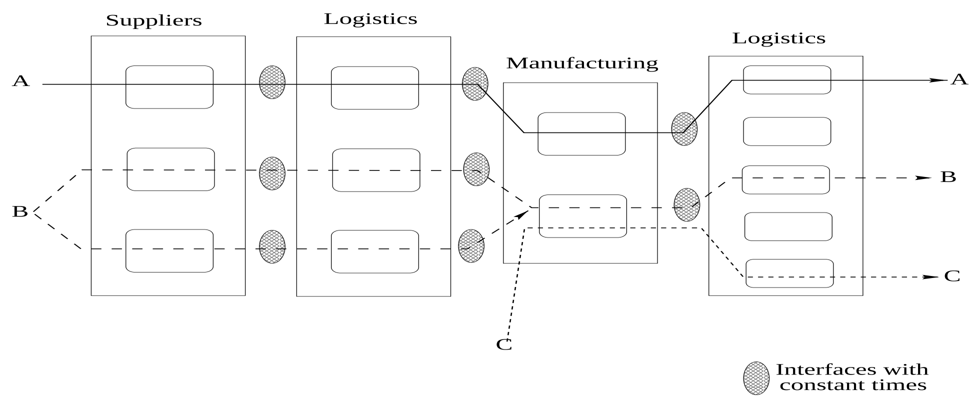

Figure 2: An illustration of the sequencing and planning problem in a SCN

ing and precedence structure along with the assignments of the corresponding processing stages to facilities of the SCN as the Bill-of-Subassemblies (BOS). What is unique in our modeling is that we allow alternate ways of doing the processing stages.

Let us consider the supply chain shown in Figure 2. The interfaces shown in the illustration, refer to work processes that need to occur when material and information are exchanged between two organizations. Refer [14] for a rigorous description. Let the logistics and interface processes be clearly defined, say, the inbound logistics is managed by the manufacturing plants and the outbound logistics by a third party contractor. The interface processes between the various members of the SCN are considered measurable and a constant time lag is added for each work process that crosses borders with a particular member. There are 3 suppliers, 2 manufacturers and multiple distribution centers. Let us consider that the SCMMS for this supply chain is done once every month. It is assumed that all processing stages are completed within this horizon. Let us further assume that there are two broad types of end products I and II, for which there are customer demands. It may be noted that these products could be shipped as finished goods from the DCs to the customer locations, or, assembled, packed and shipped from the manufacturer directly, or through third party logistics (like order C), or, sub-assembled from raw parts outsourced from suppliers, assembled in the manufacturing plants and shipped as above (like orders A or B), all depending on the inventory status and available capacity. Let orders of type A be for product I, those of B and C for product type II. It is not uncommon to have orders for intermediate products from the DCs or customer service centres. Also spare parts management for the SCN may demand that certain products be available on shelf at needed hours. Each order, thus can have its own unique routing and precedence structure. From the figure, it may be observed that some orders like B, require fork and join type of processing requirements, while some others like A flow through the SCN as if it were one straight pipe.

Given this scenario, let us consider that due-dates have been negotiated with the demand sources, priorities for various orders set, processing requirements in terms of BOS has been generated, release dates for all orders into the respective facilities is given, and available capacity at each of the facilities is known. Our objective is to firstly check for the feasibility of the SCMMS, ie., whether existing capacities at various facilities can accommodate, within the planning horizon, the given SCMMS, and secondly, if it is feasible, generate the optimal sequencing of orders at each of the facilities subject to BOS constraint and processing requirements.

The first step is essentially, rough cut capacity planning when done iteratively.

2.4 Applications of the Methodology

Since our approach is quite generic and takes the holistic view, it has a wide variety of applications, some of which we illustrate below:

1. Due date setting. This is especially useful at the customer order entry points, where the due date quoting very much determines whether the customer stays with product A or switches loyalty to product B. Delivery reliability being a crucial performance metric, it is highly desirable that the SCN meets the committed due dates given to the customers. Our methodology suits the bill, by clearly specifying if a particular order can be accommodated by the SCN.

2. If all due dates fed to our model are zero, essentially, the output schedule that is generated minimizes the total supply chain lead time. In other words, the model is suitable both to the make-to-order and make-to-stock situations.

3. Since the output from our model gives the time slices of busy periods at each facility over the planning horizon, at an aggregated level, this can be used to generate the detailed schedules at *each* of the facilities.

4. Useful for specifying capacity requirements to be quoted to third party service providers. For e.g. the number of trucks required from a contractor can be obtained by running the model with a base value. If the model gives a feasible solution with this capacity, and there is excess capacity, the number to be quoted will be just the minimal required for obtaining a feasible solution.

K	Planning Horizon
H	Number of facilities
M_{kh}	Capacity at each facility, $k = 1..K, h = 1..H$
N	Number of orders
N_i	Number of work processes per order, $i = 1..N$
I_{ij}	Successor set for each work process, $j = 1..N_i, i = 1..N$
α_i, β_i	Tardiness and earliness coefficients, resp., for each order, $i = 1..N$
α_{ij}, β_{ij}	Tardiness and earliness coefficients, resp., for each work process, $j = 1..N_i, i = 1..N$
r_{ij}, d_{ij}, s_{ij}	Release, due and earliest start dates, resp., for each work process, $j = 1..N_i, i = 1..N$
H_{ij}	Set of alternate facilities that can work on each work process, $j = 1..N_i, i = 1..N$
$t_{ijm_{ij}}$	Processing time for each work process, $j = 1..N_i, i = 1..N, m_{ij} \in H_{ij}$
S_{ijl}	Interface time between two consecutive work processes, $j = 1..N_i, i = 1..N, l \in I_{ij}$
b_{ij}	Beginning time of a work process, $j = 1..N_i, i = 1..N$
c_{ij}	Completion time of a work process, $j = 1..N_i, i = 1..N$
T_i	Tardiness of an order = $max(0, c_i - d_i)$, $i = 1..N$
E_i	Earliness of an order = $max(0, s_i - b_i)$, $i = 1..N$
T_{ij}	Tardiness of a work process = $max(0, c_{ij} - d_{ij})$, $j = 1..N_i, i = 1..N$
E_{ij}	Earliness of a work process = $max(0, s_{ij} - b_{ij})$, $j = 1..N_i, i = 1..N$
δ_{ijkh}	Boolean value = 1 if (i, j) is assigned to h at time k, 0 else. $j = 1..N_i, i = 1..N, k = 1..K, h = 1..H$
J	The objective function to be minimized
J_{AUX}	The auxiliary objective that is actually minimized

Table 1: Notation used in the formulation

3 The problem formulation

Lagrangian Relaxation [5] provides an efficient way of scheduling independent jobs with due dates on identical parallel machines, or for more complex structures incorporating precedence relationships among job processing stages [6, 7]. The integer programming formulation, albeit with non-linear objective function, facilitates the application of Lagrangian relaxation technique. Decomposition of the dual problem serves to simplify the solution at the lower level. The higher level problem is solved via a modified sub-gradient method.

We formulate the rough cut capacity planning and sequencing problem in supply chains as a deterministic discrete time finite horizon problem. Since the nonlinear programming problem that we have formulated is NP-hard, and observing that the sequencing problem that we wish to solve has a separable structure very similar to that of job shop sequencing, we resort to Lagrangian relaxation of the original formulation and solve the same. An approximate value for the resulting duality gap is also obtained.

The objective of our model is to minimize the sum of weighted squared tardiness (difference between the due date and the actual completion time) and the earliness (difference between the earliest start time of an order and its actual beginning time) of orders in the supply chain. The rationale for choosing such an objective is as follows. Orders in a supply chain typically come with their respective due dates and in order to retain customers, order filling rates and ability to stick to due dates are crucial performance measures [14]. The weights assigned to each order signifies the seriousness of the alliances that customers have with the supply chain. For e.g. orders from OEM's having alliances with sub-assembly providers can have higher weights. Missing their due dates would cost heavily for the sub-assembly providers. The other term in the objective has got to do with reducing the inventory in the supply chain. If we release an order in the supply chain before its earliest starting date, that would mean that it will be waiting in the inventory somewhere down the line. Hence by regulating the release, we control the in process inventory, thus reducing the supply chain costs. Refer to Table 1 for notation. In the model, the decision variables are the beginning times $\{b_{ij}\}_{j=1,i=1}^{N_i,N}$. Once these are selected, the other variables like the completion times, the tardiness-earliness values and the integer variable δ_{ijkh} can be easily derived. All other parameters (see Table 1) are user defined. The objective function of interest is the squared weighted sum of the tardiness and earliness for all jobs. As in [3], the original objective function J is:

$$J = \sum_{i=1}^{N}(\alpha_i T_i^2 + \beta_i E_i^2) \tag{1}$$

In order to reduce solution oscillations, it was proposed in [3] that an auxiliary objective function be defined incorporating penalties for work processes instead of individual orders. Consequently, the objective turns out to be:

$$J_{AUX} = \sum_{i,j}(\bar{\alpha}_{ij} T_{ij}^2 + \bar{\beta}_{ij} E_{ij}^2) \tag{2}$$

$$where\ \bar{\alpha}_{ij} = \alpha_{ij} + \alpha_i \triangle_{i,N_i}, \quad and\ \bar{\beta}_{ij} = \beta_{ij} + \beta_i \triangle_{i,1}\,. \tag{3}$$

In the above equation, $\triangle_{i,k}$ is defined as an integer variable equal to one if work process (i, j) is the same as work process (i, k) and zero otherwise.

The constraints for this model are three fold: the capacity constraint, the processing time constraint and the precedence constraint.

1. The capacity constraint: This constraint requires that the total number of orders assigned at time k and at a particular facility type h should not exceed the maximum available number of this facility at that epoch, M_{kh}. Note that we define capacity as the number of facilities of type h available. This number can be treated as the available hours at that facility during the time period k to $k+1$.

$$\sum_{i}^{N} \sum_{j}^{N_i} \delta_{ijkh} \leq M_{kh}.\ 1 \leq k \leq K;\ 1 \leq h \leq H; \tag{4}$$

2. Work process precedence constraint: This requires that the beginning times of the set of work processes in I_{ij} be greater than or equal to the completion time of operation (i,j) plus any required timeout S_{ijl} between work processes (i,j) and (i,l), $l \in I_{ij}$.

$$c_{ij} + S_{ijl} + 1 \leq b_{il}.\ \ \forall j = 1..N_i\ i = 1..N,\ l \in I_{ij} \tag{5}$$

3. The processing time constraint: This requires that the completion time for an order equals the beginning time for that order plus the processing time. We follow the convention that all beginning times are counted at the beginning of an epoch and all completion times denote the end of an epoch. Thus we get the following constraint:

$$c_{ij} \ = \ b_{ij} + t_{ijm_{ij}} - 1.\ \ \forall j = 1..N_i\ i = 1..N,\ m_{ij} \in H_{ij}. \tag{6}$$

3.1 Solution Methodology

The complexity of the above constrained non-linear optimization problem motivates a decomposition approach. An augmented Lagrangian relaxation approach has been used in [3] to achieve a decomposition of the job shop scheduling problem. Lagrangian relaxation is applied to the auxiliary problem formulation. For details, refer to [3].

See Table 2 for a sketch of the solution algorithm. Since the solution obtained by relaxing the constraints is likely to yield infeasible results, we incorporated a feasible schedule generating phase, similar to [3].

As regards rough cut capacity planning, the model is run iteratively as long as the orders can be processed within the planning horizon. For this, it may necessitate that we alter the capacities of bottleneck facilities, or, satisfy some orders

Step 1:	Initiate the multipliers π and η to zero.
Step 2:	For each work process (i, j) by enumeration, compute L^*_{ij} and assign δ_{ijkh} appropriately; $s_{ij} \leq b_{ij} \leq K - t_{ijm_{ij}} + 1$, $m_{ij} \in H_{ij}$.
Step 3:	Compute Lagrangian dual value.
Step 4:	Maximum iterations reached? Goto Step 5. Else goto Step 2.
Step 5:	Obtained plan feasible? Output the schedule. Else generate feasible schedule as in [3].
Step 6:	Still infeasible? Alter the capacities, or, re-schedule some orders for another plan horizon. Goto Step 1. Else STOP.

Table 2: Solution sketch for the model

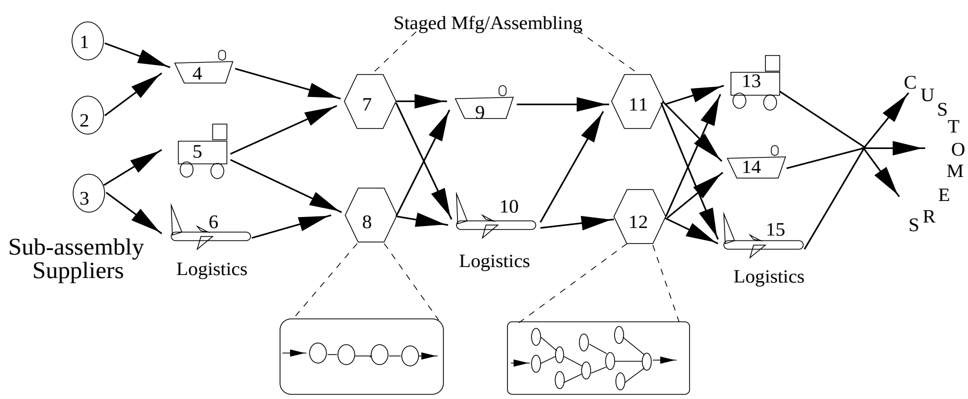

Figure 3: Example considered for capacity planning

in the next planning horizon. Our model indicates the facilities that are potential bottlenecks. We also applied the model for a supply chain with complex assembly operations and orders of several types flowing with different due date requirements and have found encouraging results.

3.2 Test results

Let us consider the supply chain for consumer products. Such products are characterized by short product life cycles, seasonal demand patterns and supply chain practices like vendor managed inventory. Let us assume that the planning horizon is 3 months and it is a single manufacturer multi retailer, multi supplier network. Typical examples are goods like fans, white goods, textiles, etc. Consider the configuration of the network shown in Figure 3. The product structure for one of the products delivered, H, is shown in Figure 4, indicating possible intermediate products which can be sold, and each component or sub-assembly is likely to have spare parts requirements. Let us assume that the inventory available at various stocking points is known at the beginning of the planning horizon. Also known are the components of demand (not shown in this paper, since the number of orders considered is large). Our method allows incorporating more than one product type in the supply chain.

See Table 3 for the partial Gantt chart that was obtained on solving this example. In this table, Order#[a,b] stands for the work process 'b' of order 'a'. From the chart, we see that facilities 13 and 14, which are two alternatives for outbound logistics have not been assigned any order. Also, the maximum exit time taken for any job is 112, which is for order number 5. Thus, if this order is a new one for the supply chain, the process owner of the supply chain can quote 112 days from today, as the due date for this order. Also, since the planning horizon was 3 months, we have overshot the same by 22 days. Thus, if we need to complete all orders in 3 months, we have to hike the capacity of some of the facilities. One alternative is to decrease logistics times at facilities 13 and 14, so that the load may be equally shared between facilities 13, 14 and 15. Another alternative is to shift some orders to be planned in this horizon to the next phase. Yet another alternative is to outsource some of the orders. We dont present them in this paper.

For the example considered, we obtained the value of the auxiliary objective for the feasible solution, J_{AUX} as 740608 while the lower bound on this is obtained as 725671, an approximate bound on the duality gap (see [3] for a definition) of 2.06%.

We also performed sensitivity analysis as to what would happen to the objective if new facilities are added, or some existing processing times are changed etc. Observe that the relative change in the objective is equal to the dual price obtained from the solution to the Lagrangian relaxation.

4 Conclusions

In this paper, we have dealt with an integrated manner in which capacity planning and sequencing of orders can be done in supply chains at an aggregated level. The rough cut capacity planning and sequencing problem is extremely useful in determining if the orders that are to be satisfied in a planning horizon can be really accommodated, given the capacity constraints and the complex precedence constraints. We presented a Lagrangian relaxation approach to this problem, clearly bringing out the ways in which this approach can be used in real world supply

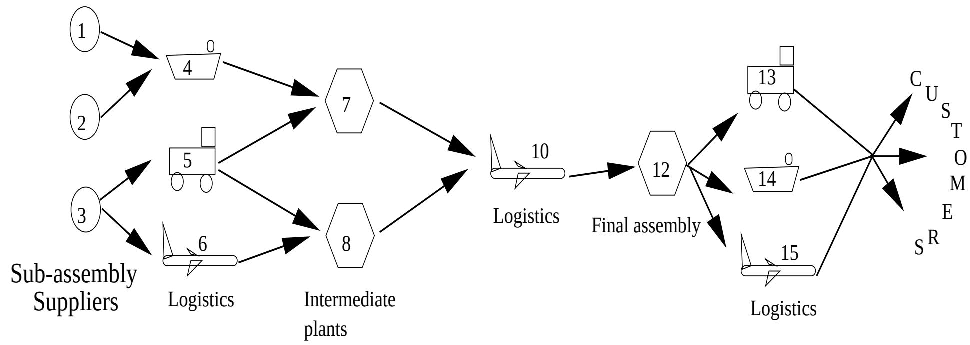

Figure 4: The supply chain and the precedence structure for product H of the example considered

chains.

Our approach is much broader in content and holistic in the sense that we consider not only the manufacturing unit but also its interactions with various other members of the supply chain like the suppliers, the logistics operators and the distributors. Since our method when used, will give the time slices of busy periods in each period of the planning horizon, it can be used for detailed scheduling at the individual facilities concerned.

As a pointer to future research, we propose the study of the capacity planning problem in a dynamic and stochastic setting, rather than a static and deterministic one.

References

[1] J. S. Boronico. The application of reliability constrained stochastic capacity planning models to the service sector. *European Journal of Operations Research*, 97(1):34–40, FEB 16 1997.

[2] K. M. Bretthauer and M. J. Cote. Nonlinear programming for multiperiod capacity planning in a manufacturing system. *European Journal of Operations Research*, 96(1):167–179, JAN 10 1997.

[3] C. S. Czerwinski and P. B. Luh. Scheduling products with bills of material using an improved lagrangian relaxation technique. *IEEE Transactions on Robotics & Automation*, 10(2):1–13, APRIL 1994.

```
For Facility# 10--------->
        From time: 57 Till time: 64 Work on Order#[8,9]
        From time: 65 Till time: 72 Work on Order#[9,9]

For Facility# 11--------->
        From time: 36 Till time: 45 Work on Order#[1,6]
        From time: 46 Till time: 55 Work on Order#[2,6]
        From time: 56 Till time: 65 Work on Order#[3,6]
        From time: 66 Till time: 75 Work on Order#[7,7]
        From time: 84 Till time: 93 Work on Order#[6,7]

For Facility# 12--------->
        From time: 22 Till time: 26 Work on Order#[10,3]
        From time: 66 Till time: 70 Work on Order#[8,10]
        From time: 74 Till time: 78 Work on Order#[9,10]
        From time: 88 Till time: 92 Work on Order#[4,8]
        From time: 96 Till time: 100 Work on Order#[5,8]

For Facility# 13--------->

For Facility# 14--------->

For Facility# 15--------->
        From time: 27 Till time: 30 Work on Order#[10,4]
        From time: 46 Till time: 49 Work on Order#[1,7]
        From time: 56 Till time: 59 Work on Order#[2,7]
        From time: 66 Till time: 69 Work on Order#[3,7]
        From time: 71 Till time: 74 Work on Order#[8,11]
        From time: 76 Till time: 79 Work on Order#[7,8]
        From time: 80 Till time: 83 Work on Order#[9,11]
        From time: 93 Till time: 96 Work on Order#[4,9]
        From time: 97 Till time: 100 Work on Order#[6,8]
        From time: 101 Till time: 104 Work on Order#[5,9]
```

Table 3: Partial Gantt chart for the example

[4] Goldratt Eliahu and Cox Jeff. *The Goal: A Process of Ongoing Improvement*. North River Press, Croton-on- Hudson, NY, 1987.

[5] M. L. Fischer. Optimal solution of scheduling problems using lagrange multipliers. *Operations Research*, 21:1114–1127, 1973.

[6] D. J. Hoitomt, P. B. Luh, E. Max, and K. R. Pattipati. Scheduling jobs with simple precedence constraints on parallel machines. *IEEE Control Systems Magazine*, 10(1):34–40, FEB 1990.

[7] D. J. Hoitomt, P. B. Luh, and K. R. Pattipati. A practical approach to job shop scheduling problems. *IEEE Transactions on Robotics & Automation*, 9:1–13, FEB 1993.

[8] E. Khmelnitsky and K. Kogan. Optimal policies for aggregate production and capacity planning under rapidly changing demand conditions. *International Journal of Productions Research*, 34(7):1929–1941, JUL 1996.

[9] Hal Mather. *Competitive Manufacturing*. Prentice Hall, Englewood Cliffs, New Jersey, 1988.

[10] W. Maxwell, J. Muckstadt, L. J. Thomas, and J. VanderEecken. A modeling framework for planning and control of production in discrete parts manufacturing and assembly systems. *Interfaces*, 13(6):92–104, DEC 1983.

[11] S. J. New, A. G. Lockett, and R. J. Boaden. Using simulation in capacity planning. *Journal of Operational Research Society*, 42(4):271–279, APR 1991.

[12] P. C. Pandey and M. A. A. Hasin. Integration of rough-cut-capacity planning with manufacturing resource planning. *International Journal of Computer Applications*, 10(5-6):271–279, 1997.

[13] A. Shtub and K. Kogan. Capacity planning by the dynamic multi-resource generalized assignment problem (DMRGAP). *European Journal of Operations Research*, 105(1):91–99, FEB 16 1998.

[14] N. Viswanadham and N. R. Srinivasa Raghavan. Flexibility in manufacturing enterprises. *Sādhanā: Academy Proceedings in Engg. Sciences*, 22:135–163, Part 2 APR 1997.

[15] T. E. Vollman, W. L. Berry, and D. C. Whybark. *Manufacturing Planning and Control Systems*. The Dow Jones-Irwin/APICS Series in Production Management, 1988.