INTEGRATED RESOURCE SCHEDULING AND SIMULATION FOR DYNAMIC LOGISTIC MANAGEMENT

ROBERTO MOSCA, AGOSTINO BRUZZONE, ALESSANDRA ORSONI

University of Genoa - Department of Production Engineering
Via Opera Pia 15, 16145 Genoa, ITALY
e-mail: {agostino, aorsoni}@itim.unige.it

Abstract: Resource scheduling is a critical step in the management of complex logistic networks. The paper proposes an integrated scheduling and simulation approach for dynamic resource allocation in complex transportation logistics. An example application, specific to the maritime logistics of the chemical supply chain, is discussed in the paper, along with preliminary testing of the system by industrial users.

Keyworks: resource scheduling, transportation logistics, dynamic logistic management, chemical supply chain

INTRODUCTION

Complex logistic networks servicing distributed production environments require efficient and flexible resource scheduling in order to meet the dynamic needs of production. Costs and risks of poor resource scheduling rise as the size and the geographical distribution of the supply chain are increased. The paper describes an integrated scheduling and simulation system for dynamic resource allocation in the maritime logistics of distributed chemical processing. In this context, resource scheduling refers to the allocation of commercial vessels types and sizes to a multiplicity of product transportation requirements subject to the stochastic variability of calendar constraints. Such constraints are concurrently determined by variable product pick-up/delivery dates, vessel availability and current location, equipment availability and set-up times at different docking facilities and port infrastructures. Simulation provides the context for scenario customization and testing of the logistic solution as interfaced to the production network. In particular the simulation module tests the feasibility of each scheduling solution and provides quantitative measures of its performance, intended as combined logistic and production performance for the specified industrial context. In the assessment of each scheduled plan the system accounts for weather conditions, influencing ships navigation times, for congestion and failures at each facility, affecting port operations times, and for variable production rates, which impact product stock and available storage capacity at each processing site. For these purposes, a dedicated database receives hourly updates on the status of the dynamic scheduling parameters such as, plant production rates, storage levels, and ships locations, directly from the operative information systems. Some of these parameters are collected on-line and in real-time (i.e. Estimated Time of Arrival –ETA– directly provided by all the ships currently operating in the network, their position through the Geographic Positioning System –GPS–, and Storage Level in each Port/Plant's Reservoir,) others are extracted from the transitional informative and management systems (i.e. calendar changes in the availability of resources and infrastructures). The database is structured to ensure that different users may create their own scenarios modifying the detailed parameter settings (i.e. capacity of pipeline Z of plant X), without introducing changes in the reference data for operative scheduling. A hierarchical user authorization procedure ensures the consistency of the baseline scenario which is the current/actual reference for operative planning an scheduling. The system has the major advantage of displaying within a single application the entire set of information required to complete the designated scheduling tasks. Scheduling solutions can be obtained which are fully compatible with the entire range of technical, logical, and regulatory constraints characterizing the actual transportation network.

SCHEDULING MODULE

Operative scheduling of the entire transportation network requires large sets of data including the full list of product flows ranked by priority and complete with all the relevant information such as, ports of origin and destination, product, quantity, loading/unloading calendar slot, estimated unloading/loading slot, and estimated navigation time. The second set of information refers to the port characteristics, for instance number of docking facilities, saturation index and possible interference/overlap for each flow included in the list. Finally, a list of ships compatible with the selected flows is required along with all the relevant ship information such as name, size, type of contract, saturation, current position, last product delivered and ETA).

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The priority index employed for ship mission ranking purposes can be calculated as a function of:

- Product flows managed by the ship mission
- Cost of the ship allocated to the mission
- Penalties associated to the given ship/contract
- Proximity index for the next loading/unloading calendar slot (difference between the beginning of the slot and the current date)

The proximity index allocates scheduling priority to the nearest ship missions in time, assuming that the cumulative effects of the stochastic phenomena concurring to determine the ETA of later ships on later missions will concurrently contribute to facilitating their fitting a feasible schedule. Equation 1 is used to determine the priority index.

$$\pi_i = \eta_{Fl} \sum_{j=1}^{j=PM} F_{ij} + \eta_S C_S + \eta_{Pn} C_{Pn} + \\ + \eta_{\Pr}\left(d_{start} - d_{now} - \gamma_{gate}\right) \tag{1}$$

In the equation

π_i = Priority of i-th ship mission/order
F_{ij} = j-th flow of mission i-th
η_{Fl} = Flow's weight coefficient on that ship
Cs = Cost of ship hire
η_s = weigh of ship hire
C_{Pn} = ship penalties by contract
η_{Pn} = weight of penalties
d_{start} = calendar slot start date
d_{nowt} = current date
γ_{gate} = slot duration in days
η_{Pr} = weight of slot proximity

Each one of the physical objects, namely resources, involved in the scheduling process has an associated calendar where busy/available times are recorded. Resources are allocated to ship missions according to their priority ranking and accounting for all the applicable constraints, these include:

accessibility constraints: requiring for instance ship/dock compatibility in terms of geometric parameters such as ship's length, width and deadweight.
product compatibility: requiring specialized procedures between product unloading and any new product loading if the two types of products are classified as non compatible for storage/ transportation.
temporal interference: related to the possible overlap of the loading/unloading calendar slots for different ships operating in the same port/dock.
production sustainability: concurrently determined by plants storage capacities and production rates: sustainability is an indicator of the number of days that production can be carried out independent of a particular ship's arrival.
resource constraints: determined by the simultaneous need to employ the same resource for different tasks such as, more than one ship per dock, multiple loading/unloading tasks per pump/pipeline/equipment, multiple connection requirements for a pipeline segment enabling the connection to different reservoirs.

When the application is run in the automatic mode, if a conflict and/or violation of the constraints occurs, the scheduling problem is flagged out to the user and possible solutions are suggested based uniquely on cost effectiveness considerations. However, more experienced users may have reasons to force some of the constraints, knowing for instance that the deadweight of a particular ship is compatible with the accessibility requirements of a given dock if the ship is carrying half or less of its maximum capacity: therefore when run in semi-automatic mode, the system allows for user intervention in forcing some of the pre-set constraints. The allocation of a ship to a given product flow grouping automatically changes the saturation levels of both ship and docking facilities. Color coding is used in the interactive operation mode to display the saturation level of each resource: green (less then 50%), yellow (up to 75%) and red (more than 75%). By clicking on any of such indicators the program displays a multilevel Gantt chart for each object (ship/facility) where all the busy time slots, relevant to the scheduling horizon, are recorded. The different objects determining the occupation state of each resource/facility are displayed on the Gantt Chart and may be moved by the user causing the recalculation of the entire set of parameters for constraint verification/satisfaction purposes. Constraint and interference verification enables the identification of potential conflicts, however the interactive scheduling mode accepts the definition of highly incompatible ship missions. The stochastic variability associated to each component/operation, in fact, can often create conflicts even within perfectly timed missions, therefore the identification of conflicts does not have blocking consequences in the scheduling process nor does it force the user to make immediate changes to rectify the situation. Temporal overlaps are pointed out by the system and recorded in the calendars of the relevant objects where each occupied slot is specified in terms of start/end dates, designated user and purpose.

Conflict management, as in the case of overlapping calendar slots for two or more ships with respect to a same docking facility, is entirely handled assessing the cost implications of each alternative solution at the level of the entire scheduled plan (i.e. accounting for secondary and tertiary impacts). The allocation of docking priority is the result of a negotiation among the owners/operators of the different ships (or tradeoffs, if the ships are operated by the same company) taking into account the daily costs of each ship, possible penalties, the costs of downstream delays, and the sustainability of production. The cost of the entire scheduled plan is considered on three temporal horizons: short, medium and long term, each one of them carrying a different weight in the performance evaluation procedure of the current schedule. Short term costs have higher impact on the performance of the current schedule, therefore they carry a higher weight in affecting scheduling choices. Typically the short term scheduling horizon is fixed to three months, the medium term is approximately six months and the long term is one year. As shown in figure 1, risk analysis is performed in order to estimate possible delays in loading/unloading calendar slots and the likelihood of finding the designated docking facility busy at the time of ship arrival.

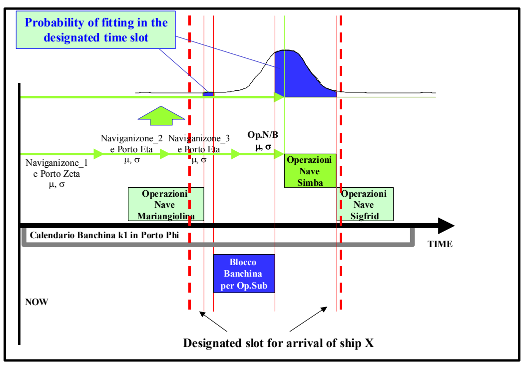

Figure 1: Dock Calendar: Example of Risk Analysis

Any change introduced in the scheduling parameters, such as the ETA of a given ship or the loading/unloading calendar slot for a given product, triggers the re-scheduling of all the events of resource occupation for the corresponding ship mission and causes the update of the relevant object calendars (i.e. the change in ETA to the loading port/dock causes changes in the ETA and saturation levels at the corresponding unloading port/dock). External events such as maintenance, failure, decommissioning of any of the resource, originating in the company but not within the logistic management function, need to be systematically transferred to the system's database as they introduce important changes in the scheduling constraints.

SIMULAITON MODULE

The scheduled plan, as generated by the scheduling module, is only statically verified because the module alone does not account for the stochastic variability of either process parameters or external factors (and their synergies i.e. late/early arrivals and early/late completion of each sequence of operations). For instance, the preliminary schedule fails to account for the probability that the ship may find docking facilities and equipment busy, due to the late arrival of other ships. Such a probability, instead, is fully accounted for by the simulator which tracks the detailed evolution of the scheduled scenario.

The output of the simulation run is a detailed evaluation of the performance measures associated to the scheduled scenario; given the stochastic nature of the simulation model, multiple replications of the same scenario (using different random number generation seeds each time) lead to an estimate of the experimental error, of its impact on the simulation output, and of the associated risks.

In the simulator each physical component of the logistic network (e.g. ships, docks, equipment) and of the production interface (e.g. plants, reservoirs) is modeled as an object described by a set of both static and dynamic parameters. Along with such objects there are purely logical objects such as, Routes, Tactical Missions, Ship Missions, Product Flows, and Calendars, which are user-defined and have specified interactions with the physical objects.

The nature of the objects, their interactions, and their mutually imposed constraints suggest that the basic simulation logic should be both dynamic and discrete-event-based. In other words, the time advancement mechanism is set by the occurrence of un-conditional events, which in turn create the conditions for conditional events to take place, leading to variable time steps. Because the sets of coordinates describing the position of each ship need to be continuously updated along with its Estimated Time of Arrival (ETA), while simulating all the events involving the different system objects, the time advancement mechanism has to be "mixed" in nature, enabling for punctual re-calculation of the continuous variables at each time step. The continuous variables include:

ETA (along with positional and kinematic variables) for each ship currently in navigation during the time period included between the two most recent events, considering the entire set of boundary conditions influencing the motion of the ship, and their variability, according to the following equation:

$$ETA_j(t_i) = ETAj\,(t_{i-1}) - Vel_j\,(t_i - t_{i-1}) \qquad (2)$$

where

- ETA_j = ETA of ship j at time t_i
- Vel_j = speed of ship j in the period $t_{i-1} \rightarrow t_i$
- t_i = time of occurrence of event i

Storage levels for each reservoir during the period between the two most recent events, considering plant production rates as well as import/export activities.

$$LS_j(t_i) = LS_j + \Sigma[\, F^j_k\,(t_i - t_{i-1})] \qquad (3)$$

where

- LS_j = Storage Level of reservoir j at time t_i
- F^j_k = product flow j in the period $t_{i-1} \rightarrow t_i$
- t_i = time of occurrence of event i

Statistics update based on the time elapsed between the two most recent events, considering the current status of the simulated objects.

The stochastic nature of the simulated process is accounted for in terms of

- Navigation times
- Plant production rates
- Import/export volumes
- Component/Ship/Equipment Failures

Probability distributions are associated to such variables, building from historical data, and the Montecarlo technique is employed to extract punctual values out of such distributions during the simulation run. The types of distributions included in the simulation, by category of representation are

- Component Failures → Negative Exponential
- Component Repair → Standard Bell-Shaped
- Plant Production Rates → Beta
- Navigation Times → Beta

The active objects of the simulation are ships, product flows and orders. Evenly distributed statistics sampling events are designed in order to ensure a uniform description of the simulated processes throughout the simulation run. Such events are exactly the same in nature as other process events, but they are only intended to capture pictures of the logistic situation at time intervals of approximately one simulated day.
The physical interactions among ship, dock and loading/unloading equipment are represented in figure 2. Loading and unloading times are functions of the actual product quantity and of the flow rates managed by the available pumps.
As indicated in the figure, the model accounts for simultaneous product loading/unloading operations: as many as allowed by the product-compatible pumps/pipelines available on the dock. If the ship needs to load products from empty reservoirs or unload products into full reservoirs, it enters a conditional wait state until the reservoir in question can be accessed for the designated operations.

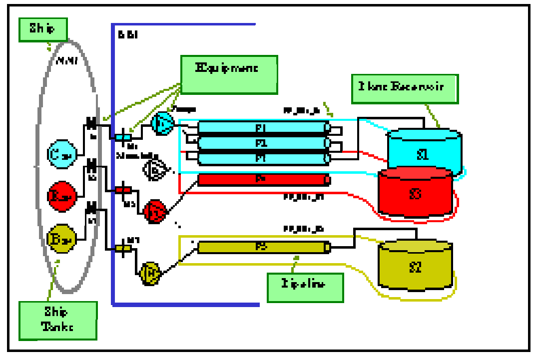

Figure 2: Dock-Ship-Equipment Interactions

Accessibility and compatibility constraints require the simultaneous availability of all the equipment connecting the ship's tank to the plant's storage reservoir and each of the pieces of equipment involved to be compatible with the type of product to be loaded/unloaded. Different combinations of pump/pipeline are possible, as long as they lead to the designated product reservoir and that they are compatible with the product to be transferred.

CONCLUSION

The paper presented the key features and implementation issues of an integrated scheduling and simulation tool for dynamic resource allocation in complex supply chain logistic applications.
The system, currently at the final implementation stages in a large chemical company has been preliminary tested by industrial users. "Turing tests" have been performed to validate the system: such tests involve the participation of Subject Matter Experts (SMEs), namely maritime logistics experts from the company, and requires them to discriminate between schedules developed by the system and schedules developed by human planners. Simulation-based testing shows that the scheduled plans proposed by the system are usually feasible in reality, however they are typically more conservative than the schedules proposed by human experts, thus leading to marginally lower ship capacity utilization and slightly higher costs in favor of higher production sustainability (i.e. negligible risks of stock-out and over-stock events at the production sites.). Such results call for fine-tuning of the decision heuristics built into the scheduling module and of the coefficients weighing the different components of the target cost function.

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