Ethylene furnace scheduling

One solution to the logistical constraints seen in ethylene plant furnace scheduling is technology that automatically generates multiple optimised schedules for schedulers to analyse and quickly select the best one to be executed

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Ethylene furnace scheduling determines the optimum furnace decoke schedule and feedstock allocation to the furnace section of an ethylene plant. The scheduling activity is typically done on a daily basis to meet continuously changing feedstock supplies and production demands. Currently, it is mainly done manually. Production departments lack the tools to find feasible schedules, let alone to compare multiple feasible schedules and choose an optimum one. The proprietary Production Scheduler has been extended to include ethylene plant complexities using a new approach to solve the problems of logic, quantity and quality.

Ethylene furnace scheduling lies at the heart of every production scheduling activity for a petrochemical complex. The ethylene plant is the key source of intermediates for all downstream production units and its operation directly affects downstream production quantities and qualities. Production scheduling has traditionally been viewed as being somewhere in between production planning, real-time process optimisation (RTO) and advanced process control (APC). Where planning is aiming to optimise the feedstock purchase, production scheduling deals with the optimal allocation of the feedstock and optimal severity profile over time. APC/RTO then optimises the utilisation of those feedstocks.[1-3]

The key technologies used in planning software include successive linear programming (SLP); in real-time optimisation software they include successive quadratic programming (SQP); and in advanced control software quadratic programming (QP). However, until recently, the key technology used in commercial scheduling software was sequential modular simulation with some minor production rules programmed in by the implementer using macro-type languages, usually at configuration time.

The formulation of the production scheduling problem is based on three main axis or dimensions, which is in fact a decomposition of production itself. The first axis is quantity. Petrochemical complexes must balance available hydraulic and hold-up capacity, given that most of the materials being processed are either gases or liquids. This means that flows and inventories (known as extensive variables) must be properly sized and carefully managed throughout the entire plant operation. The second axis is quality, which is defined as the "conformance to product specification". However, quality is considered one of the intensive dimensions of production, which includes composition, properties and conditions. Examples of compositions include the butadiene content in the C_4 fraction and the benzene content in the aromatics of a stream, where conditions may include temperature, pressure, direction and flow rate. The third and other intensive axis of production is logic, which deals with the operating details, rules and policies of how to assign resources to operations, how to sequence or order operations, and how to timetable operations. Logic has always been a part of petrochemical production, yet until now it has not been formalised and structured into a cohesive and clear framework, complementing the other two production dimensions of quantity and quality.

In essence, logic has been the missing link with regard to understanding and clarifying the anatomy of the production scheduling problem. From an optimisation perspective, simultaneously solving quantity, quality and logic variables subject to quantity, quality and logic constraints is intractable for realistically sized problems of any significant business value.

In the solution presented in this article, two optimisation subproblems, referred to as a logistics problem and a quality problem, are pragmatically solved in series. The logistics problem is solved for quantity and logic using mixed integer linear programming (MILP) first, then the logic variables are fixed, whereas the quality problem is solved using SLP for quantity and quality. It is also possible to think of the logistics problem as the physics of the overall problem, and the quality problem as the chemistry of the overall problem.

Logistics optimisation

As mentioned, logistics is defined as the quantity and logic details of production, which is actually no different to logistics operations performed by transportation companies, such as pipeline and trucking carriers. The reason for this similarity arises from the fact that in petrochemical production materials also have to be moved from location to location in order for the different stages of production to take place. The most interesting aspect of the logistics is the different type of logic variables and constraints. More than 30 logic constraints have been identified that may or may not be observed at any one petrochemical production, but they nonetheless comprise a somewhat comprehensive and evolving set.

In fact, there are only three independent logic or binary variables necessary to schedule a complex petrochemical operation, and these are modes, materials and moves. Modes are the different activities that a particular process unit can be operated in, such as decoke or high severity operation. Materials are the activities that a pool unit can be operated under. Pool units are simply equipment that can accumulate inventory, such as a tank, sphere or cavern. Material service changes can be scheduled for multi-product or swing tanks. Moves represent the transfer of material from a process unit to a pool unit, for example. Moves are operations between equipment and modes, and materials are operations on or in equipment. Each of these instances of modes, materials and moves also has three other dependent binary variables attached to model the omnipresent issue of transitions (setups, switchovers or changeovers). Every mode, material and move logic variable has a startup, shutdown and switch-over-to-itself marker variable to indicate and account for when and for how long a particular activity is active. These are crucial to specifying and optimising the schedule for the purpose of logistics feasibility and optimality.[4]

Logic and time details

While it is not possible to present all of the possible logic constraints, the following list of logic and time details will provide a good understanding of the basic concepts. Previously, these rules were considered as experience or knowledge held by the scheduler and are the reason scheduling was seen more as an art form than a science:

— **Semi-continuous flows** Flows between equipment can be intermittently operated, especially if there is more than one way to transfer material from point A to B. Semi-continuous flows can be either zero or must lie between some range specified by lower and upper hydraulic constraints

— **Single-use constraint** Most equipment can only perform one task at a time and hence is classed as what is known as a unary resource. Examples of unary resources are feedstock headers, which can only accept one type of naphtha at a time, or an ethylene furnace, which can either be in decoke mode or operation, but not both at the same time.

— **One flow-in and one flow-out** For certain pieces of equipment, there can only be one flow-in (or one flow-out) at anytime, where multiple flows-ins are not allowed within a time interval

— **Fill-draw delay and draw-fill delay** For pool units, there can be the restriction that after a fill a draw-out of the vessel cannot occur until a certain amount of time has elapsed. This is useful, for example, when a naphtha tank must stand for 24 hours after a flow-in before a flow-out can be scheduled. The opposite of fill-draw delay is draw-fill delay

— **Minimum and maximum run lengths for modes, materials and moves** Operations on or between equipment may have a minimum and/or maximum amount of time they can be active. Minimum run length specifies the minimum amount of time an activity must be active if scheduled or executed, where the maximum run length specifies how long it can possibly last

— **Switch over when full or empty** This is useful for pool units when either filling or drawing material to/from a vessel. If a naphtha is being delivered from a pipeline to a tank, it may be preferred to have it switch over to another tank only after that tank is full, instead of switching over when it is, for example, half-full

— **Material or product downgrading** Downgrading of a more valued material to a lesser-valued material is called downgrading. Downgrading is sometimes required when, in order to meet a product lifting demand order, a material of higher quality and value must be produced and downgraded to the lesser-valued material

— **Marine vessel loading (or unloading) arrival and departure** The majority of purchased feeds and saleable products are received and shipped by either pipeline or marine modes of transportation. The key logic constraints involved in handling the arrival and departure of marine vessels (VLCCs, barges and so on) are respecting the earliest and latest expected arrival and departure times (subject to up-to-the-minute weather forecasts) and the handling of the loading/unloading of the cargo (perhaps in multiple holds) over the laycan or duration at the dock, where demurrage costs are minimised at all times.

There are two approaches to the modelling of time for logistics optimisation: discrete-time and continuous-time modelling. Planning and scheduling both imply a temporal dimension to the decision-making problem. Discrete-time modelling slices time into known intervals of either equal or unequal duration, where every operation for every piece of equipment will either start, stop or continue on this predefined timetable (similar to a regular shift schedule for operators in the plant). Continuous-time modelling must also slice time, but it is done as part of the optimisation, where the start and end times for the intervals are degrees of freedom in the MILP. This means that in continuous-time solutions every operation on every piece of equipment will have its own timetable. In contrast, discrete time has a more regimented co-ordination of the plant according to a master timetable. Continuous time is sometimes referred to as event-based, used in the context of scheduling simulators. However, there is a clear distinction between event-based simulators and continuous-time optimisers and the two should not be confused. For ethylene plants, the furnace run length, decoke time and maintenance time should be considered.

Quality optimisation

Optimising the qualities, subject to quality specifications and quantity balances and constraints, is (as mentioned) a post- or fine-tuning optimisation after the logistics optimisation has been solved. An interesting aspect of the logistics optimisation is that not just one solution is found during the MILP search; many optimised solutions can be retained. The reason for keeping several solutions is that the best logistics solution may not find the best-quality solution. Hence, in order to increase the likelihood of finding quality feasible solutions, the use of multiple logistics solutions is required, which is an innovative feature of the scheduling technology used in this discussion.

As discussed, all the logic variables are fixed (ie, mode, material and move decisions over the scheduling horizon) before solving for quality, on the grounds that simultaneous quantity, logic and quality optimisation is not possible using even the latest and greatest implementations of mixed-integer nonlinear programming (MINLP) codes. Although not all of the possible quality constraints are presented, the following list provides a good understanding of the basic concepts:

— **Cracking severity** Setting the cracking severity affects both the yield spectrum and the fouling rate of the furnaces. These severities need to be set per feedstock type and furnace design

— **Time-varying yields** Ethylene furnace yields are not constant over time, even if feedstock quality and operating conditions are kept the same. Due to the fouling that occurs in the radiant coils of the furnace, the yield pattern will change[5]

— **Product specifications** Final products need to comply with quality specifications. For an ethylene plant, this could be the benzene content in the C_6 cut or the butadiene content in the C_4 product stream.

There are essentially three types of quantity constraints: flow rate, flow and inventory. Each of these has continuous variables associated with them in both the logistics and quality optimiser formulations:

— **Flow rate** These are capacity constraints associated with a movement's process and transfer-type equipment, such as pipestills, headers, line segments, pumps and valves. They specify how much material can flow within a certain amount of time through the piece of equipment and are defined by upper and lower constraints

— **Flow** These constraints specify a quantity of material that can be transferred from one piece of equipment to another. They extend the flow rate bound to fully describe a supply or demand order. Knowing the rate and the quantity determines the duration. Both flow and flow rate constraints are associated with a connection between a source and destination piece of equipment and ultimately relate to the underlying limiting or shared transfer-type piece of equipment that moves the material from the source to the destination

— **Inventory** These constraints are capacity constraints for inventory-type equipment, such as spheres, tanks or drums. They specify how much material can be stored in a piece of equipment and are defined by an upper and lower bound.

These types of quantity and quality formulations are also similar to planning models, in that they can be classed as pooling problems (found in the operations research literature), except that there are usually many more time periods required. It is very rare to have industrial planning models with more than 1–10 time periods. However, approximately 100–1000 time periods are required to achieve production scheduling optimisation. The solution to these large nonlinear and non-convex models would not be possible without Honeywell's two-phase approach. The fact that these problems are non-convex implies that only local optima can probably ever be found, which is the reason for generating optimised and not optimal schedules.

It is possible to solve timely and efficient models with many time periods, because, in the planning models, stream flows between equipment or aggregated equipment can vary between zero and some upper limit. The problem occurs when stream flows can go to near-zero and the disposition is deemed to be non-economical or non-effective at either increasing profit or alleviating a constraint violation. This cannot happen in the Honeywell scheduling framework because of the fixed logic paradigm. Streams opened in the logistics problem are also forced to be open in the quality problem, providing a much more stable first-order derivative matrix (Jacobian), which provides a more consistent search path to the solution. This helps avoid nonlinear flow/no-flow decisions or disjunctions, which can require an enormous number of iterations. Streams closed in the logistics are not generated in the quality problem, which substantially reduces the size of the problem, making it easier to solve because there are fewer degrees of freedom. It is this simple implementation detail that permits the solving of some of the largest nonlinear optimisation problems in industry today.

Objective function

Given that it is scheduling optimisation that is being performed, a suitable objective function needs to be described. The objective function is defined to include three terms of profit, performance and penalties. Gross profit is well known to be revenue minus feedstock and holding costs, which is maximised. Performance is set up to include the minimisation of the number of modes, materials and move operations in the future. This includes minimising all startups, shutdowns and switchovers to others (transitions). If a schedule can be generated that meets all of the supply and demand orders of the system using a parsimonious number of operations it is deemed as a good schedule.

Penalties account for all of the possible true and/or apparent imbalances in the system, given the model and data supplied to the optimisation problem and the ability of the MILP search to find solutions. A system can be truly feasible, but the search may not be able to find a feasible solution in the allotted amount of time or the starting position (ie, neighbourhood). On the other hand, a problem could be specified that has gross errors in the input data or parameters, which causes the optimisation to declare the problem as infeasible (ie, non-zero penalties exist). Penalties are also sometimes referred to as infeasibility breakers, safety valves and elastic or artificial variables and are invaluable in the diagnosis of either true or apparent infeasibilities. It should be pointed out that penalties expose the effects of errors, but cannot uniquely identify the root cause or underlying fault.

A typical logisitics penalty associated with ethylene producing is minimum run-length violation for a particular cracking furnace. This means that the logistics optimiser would like to pre-empt a particular mode (ie, shut it down and switch to another) because the yields are decaying too rapidly for it to be continued as a viable operation on the furnace, producing enough product to meet downstream demands. A typical quality penalty would be an excursion from a coil-outlet temperature (COT) operating condition (upper-bound). Given the current mode on the furnace, the quality optimiser would prefer to take a penalty on increasing the COT to raise the yield of a particular product instead of backlogging a demand order for the product.

Solution technology

Our approach is to use multi-period SLP, similar to SLP technologies instituted in planning software, such as in the Refinery and Petrochemical Modeling System (RPMS) from Honeywell Process Solutions. However, the SLP code currently implemented is a relatively new product from Dash Optimization Inc, called Xpress-SLP, which is an integrated solver linked to a state-of-the-art modelling language. The planning software mentioned does not have this type of tight integration (in memory) between the modeller and the solver, making the time to generate these very large-scale models almost unnoticeable to the scheduling user. The other benefit this technology provides is the ability to quickly model complex and difficult logistics and quality constraints algebraically without having to use table-driven input forms.

Modelling technology

Modelling the production of a petrochemical complex can be achieved using methodology described in other previously published articles.[6,7] The flowsheet of the production can be built either graphically or using tabular displays in the proprietary Production Scheduler. A typical representation of a plant model is shown in Figure 1. Connections between units in the context of unit operations is handled easily by sophisticated modelling technology. A library of unit models is available, and third-party models such as Technip-Coflexip's rigorous ethylene

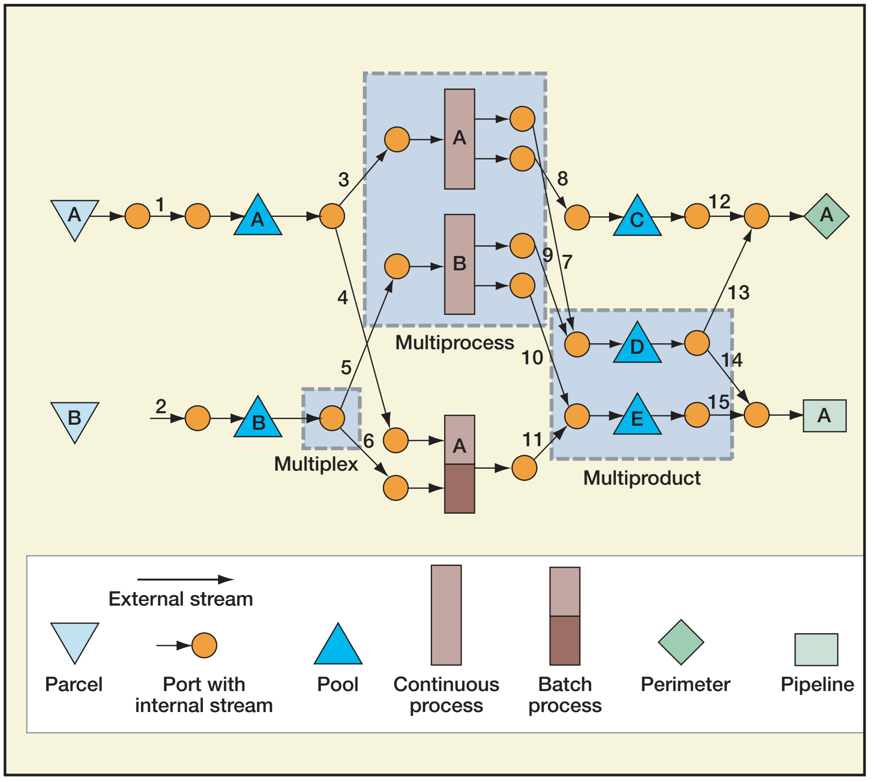

***Figure 1** Production flow network example*

furnace simulation program can be embedded as meta-models.

Potential benefits

There must always be benefit to pursuing a solution to a problem when rational thinking is involved. Better scheduling via better scheduling optimisation has many tangible and intangible benefits. Predicting and quantifying the value of intangible benefits is difficult, because they are usually anecdotal and sometimes unknown at the start of the implementation. Hence, the benefits listed in this discussion are more tangible in nature, given that these must form the basis of the benefit assessment before any expenditure can be made on a solution.

There are arguably three major types of disturbance that affect a petrochemical production unit at any time during its operation. These are feedstock quality and quantity variability, ambient temperature changes and equipment failure. Malfunctions of equipment can cause serious production slow-downs or outages, including safety concerns, and are normally mitigated by sound maintenance practices, such as a total preventative maintenance program (TPM). Seasonal and ambient temperature swings also disturb the stability of operations and are attenuated through providing increased cooling capability and improving controls, provided it is understood that ambient temperature variations are a special-cause factor in degrading the performance of the petrochemical complex.

Variation in the quality of the naphtha mixtures charged to the ethylene plant, for example, can have a serious effect on a petrochemical complex. For this reason, one of the most important aspects of better scheduling is to co-ordinate and organise the overall production environment, closely managing both the quantity and quality variables of the internal suppliers and customers, subject to quantity, quality and logic constraints, as mentioned. The following is a short list of possible benefits:

— **Reduction in the quantity and quality target variability** Reducing the quality target variance should be at the top of the list for improvements. Deviations from quality targets should be minimised in order to charge the downstream units with a steady mixture of feedstock. It also makes good sense to run the process units with a relatively constant flow rate for as long as possible. This can be a difficult undertaking without proper scheduling and control co-ordination, especially when many upstream unit streams feeding downstream units are on level control

— **Improvement in the ability to generate more than just feasible schedules** For those plants that are tightly resource constrained due to previous cost-cutting initiatives, for example, it may be an arduous task to generate a feasible schedule for the immediate future using simulation tools. It is always beneficial to have an automated scheduling application generate in seconds what would take a human scheduler hours to construct. Multiple "better than feasible" or what is known as optimised schedules may be presented, which meet the production goals for selection by the scheduler. The effect of not being able to generate feasible schedules means that either the supply scenario must be changed or the demand must be altered by decreasing or increasing the unit charge rates. Unfortunately, both of these alternatives are undesirable for various reasons

— **Consistency of schedules** A common problem in production scheduling is that there are usually only one or two skilled schedulers who can schedule a petrochemical production effectively. When these individuals are sick or on holiday, it is difficult to backfill with other appropriately trained schedulers. Moreover, if this occurs, the schedules generated by the replacements can be widely different, to the point where they may be infeasible. An automated scheduling tool alleviates some of these issues, since schedules are made to satisfy the same business logic and reflect the same constraints and limitations

— **Visibility of the production schedules throughout the organisation** Finally, given the use of Internet technologies, it should be standard fare now and in the future to distribute the official schedules online, so that managers, operators and engineers can all view the same production program for the next few days or weeks. Although this can be easily accomplished with spreadsheets and simulators, what is not always possible with these solutions is the ability to look into the future and to show the longer-term schedules to those who can take advantage.

Beyond just simulating a production schedule, the proprietary Production Scheduler automatically generates multiple optimised schedules in a matter of seconds and provides schedulers with the information needed to analyse and quickly select the best schedule to be executed. Competing products can only go as far as simulating schedules, relying on scheduling personnel to manually select an optimal schedule with limited guidance.

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