UOPSS: A New Paradigm for Modeling Production Planning & Scheduling Systems

Danielle Zyngier, a Jeffrey D. Kelly, b
aPEQ/COPPE/Federal Univ. of Rio de Janeiro, Rio de Janeiro, Brazil
bHoneywell Process Solutions, 85 Enterprise Blvd, Markham, ON, L6G 0B5, Canada

Abstract
This work highlights a more general paradigm for the representation of advanced planning and scheduling (APS) systems called the unit-operation-port-state superstructure (UOPSS). It is based on extending the P&ID and PFD of a plant or process to explicitly incorporate the procedural aspects of production. We believe that UOPSS has a more natural and simpler ability to account for capacitated problems with limited connectivity and compatibility. It can be applied to model problems in both the batch and continuous process industries including dimensional processes found in the paper, metals and meat processing industries. As such, UOPSS can be considered as a benchmark for modeling APS problems. Further to the modeling structure, this work also proposes a comprehensive data architecture that enables the use of the models across different APS cycles with minimal change (i.e., static model with dynamic data).

Keywords: Planning, scheduling, decision-making, modeling, optimization.

1. Introduction
Representing the details of any manufacturing system requires both the physical layout of the environment, usually represented by a piping and instrumentation diagram and/or a process flow diagram, as well as its procedural characteristics such as modes of operation of equipment (tasks) where these combine together to represent both the structural and behavioral aspects of production as a whole. The two most prominent approaches for the representation of production systems in the Chemical Engineering literature, namely the state-task network (STN) (Kondili et al., 1993, Shah et al., 1993) and the resource-task network (RTN) (Pantelides, 1994), originated from sequential batch-type production in which a sequence of tasks are performed on renewable (units) and/or non-renewable resources (states). These representations however have difficulty when incorporating some peculiarities of many industrial systems such as limitations in multiproduct storage capacity, limited connectivity between different multipurpose equipment in different tasks and compatibility restrictions when sequencing changeovers. To overcome some of these issues, the maximal STN (m-STN) was proposed (Barbosa-Povoa & Macchietto 1994) whereby existing connectivity in the plant is taken into account explicitly through the consideration of states entering and leaving a task respectively. A relatively recent representation of the production network is given by the unit-operation-port-state superstructure (UOPSS) (Kelly, 2003, 2004, 2005b, 2006). UOPSS is similar to a process flowsheet whilst still including the necessary procedural characteristics. Similar to a flowsheet, it makes explicit different types of units (equipment) and operations (tasks). States may also serve the purpose of modeling both renewable and non-renewable resources as in the RTN. Similarly to m-STN, UOPSS uses the concept of inlet and outlet states by adopting inlet and outlet
ports i.e., the unambiguous entry and exit points of states into and out of processing equipment. One of the key differences between m-STN and UOPSS is that the physical entry and exit ports to and from a piece of equipment are considered explicitly in the latter, i.e., ports are directly attached or incident to these units. If two streams are connected to the same inlet port they are assumed to be mixed or blended in an uncontrolled fashion (i.e., no blending recipes are applied). Conversely, if two streams leave the unit through the same outlet port these streams are assumed to have passed through an uncontrolled splitter. The concept of inlet ports as being mixers (uncontrolled blenders) and outlet ports as manifolds (uncontrolled splitters) is also shown in Pinto et al. (2000). This is of particular relevance when modeling certain types of convergent and divergent flow path equipment in the process industries like blenders and separators. Different from the previous network representations (STN, RTN, m-STN), which are primarily batch-process oriented, UOPSS is agnostic with respect to these processing characteristics of production and thus makes it a more natural representation especially when there is a mix of both batch and continuous processes within the same flowsheet.

With respect to the variables in the decision-making system, these can be categorized into quantity (e.g., rates, flows, charge, batch or lot-sizes, yields, etc.), logic (e.g., setups, startups, shutdowns, switchovers, etc.) and quality (e.g., densities, components, properties, conditions, etc.) variables. This concept has been presented by Kelly (2005b) as the quantity-logic-quality (QLQ) phenomena which is very amenable for use within the UOPS superstructure and is briefly described in this paper.

The model structure of the manufacturing system is not complete without the equally relevant topic of data and its interface between the model and the ever-changing environment around it. In planning and scheduling systems, information regarding incoming raw material supplies and outgoing customer demands are subject to change in an hourly, daily or monthly fashion. Other information regarding plant activities such as preventative or corrective maintenance operations as well as production orders can occur frequently and also need to be respected in the decision-making. This paper proposes an architecture that is able to efficiently handle these events without needing to modify the underlying model.

Finally, it is important to note that the proposed modeling system and data architecture have been implemented in a commercial product since 2002 (Kelly, 2003) in Honeywell’s Production Scheduler with over 45 industrial clients spanning several different industrial sectors

2. APS Model Structure

Production can be described by the combination of its physical and procedural characteristics. The physical description of production encompasses the pieces of equipment that are involved in production as well as the physical linkages or connections between these units. Being explicit about the physical characteristics so that limited capacity and storage is accounted for is an important aspect. The physical inlet-and outlet ports (or points of entry to/exit from a unit) enable the user to describe constraints such as only one flow in/out of the unit at any point in time and to better describe the material cuts in separation units such as distillation towers. And there may be different types of ports such as stock, signal, utility, utensil, time, etc. It is also important to overtly describe the physical connections in the system also known as “arcs” in a directed graph. This is especially true for systems in which connectivity
affects manufacturing options such as systems with flexible connections between pieces of equipment known as routes, usually found in pipe-less plants. The procedural characteristics of process units refer to the transformations or processing steps that the raw material must go through in order to become a final product, whereas for storage elements (storage tanks, warehouses, etc.), the procedural aspects usually refer to the type of product that is being held. The ports of a system inherit the procedural characteristics of the unit they are attached to. The procedural connections between elements restrict the possible production paths or recipes that the material can follow in manufacturing. For instance, 2 interconnected processing units, Unit 1 and Unit 2 (U1, U2), with 3 modes of operation each (O1, O2 and O3), will usually only have 3 procedural connections between them, out of the 9 combinatorial possibilities: {U1-O1 to U2-O1}, {U1-O2 to U2-O2} and {U1-O3 to U2-O3}. In order to properly represent production, both the physical and procedural characteristics must be combined in a unified framework. For that purpose, the aforementioned generic representation frameworks were devised such as STN, RTN, m-STN and UOPSS.

Decisions in APS problems refer to three types of variables: quantity, logic and quality. Quantity variables are continuous variables, and can either be extensive such as flows, charge/batch sizes and inventories, or intensive, such as yields, recipes and ratios. Intensive logic variables are binary variables and relate to the logic decisions of assignment, timing and sequencing of production, such as process-unit start-ups, shut-downs and switchovers-to-itself and to others, whereas extensive logic variables relate to the timing of activities such as process-unit uptime and downtime durations.

For many manufacturing systems, in particular for Chemical Engineering processes, it is of paramount importance to take quality information into account for making decisions. Quality data may refer to material properties (% sulfur, octane number, etc.), components within a material (such as pseudo-components) or operating conditions of a piece of equipment (e.g., temperature, pressure, etc.). This type of information is needed when making decisions based on specifications of a final product. Most commercial production planning products consider at least some level of quality information in the models but they cannot properly represent the complexity of scheduling problems in particular with respect to the logistics aspects.

From the logistics perspective, units vary in the duration of their fill-hold-draw stages (Zygier and Kelly, 2009). Material enters and leaves continuous process units constantly and simultaneously while the unit is running. Batch process units on the other hand are filled with material which is then held for a fixed or variable amount of time while transformations take place and then final product is drawn from the unit. Inventory units are very flexible since material is allowed to flow in and out usually with no specific timing restrictions. For this reason, inventory units usually introduce degeneracy to the problem due to the potentially large number of equivalent optimal solutions possible. Pipelines transport material sequentially from one point to another. These units obey the first-in, first-out (FIFO) model, where the first material to enter the pipeline is also the first one to leave. Parcel units are industrial shipping vessels in which material is loaded at the original dock, unloaded at one or more customer docks, and then returns (with some delay) to the original loading place. Another type of unit is the pileline unit which is extensively used in solids processing industries such as mining. A pileline is a last-in, first-out (LIFO) type of model which is applicable when there are different piles of material laid out in a yard or warehouse. Due to (limited) accessibility issues, the last pile of material added to the yard will be the first one to be
reclaimed from it. For more details regarding the modeling of the aforementioned elements the reader is referred to Zyngier and Kelly (2009).

3. APS Solution Architecture using UOPSS

APS is a decision-making task for all process industry plants that receive feed-stocks from suppliers, subject these feed-stocks to some level of processing (i.e., mixing, reacting and separating) and distributes the processed product-stocks to customers or other plants whilst managing intermediate-stocks or work-in-process. Decisions made during scheduling for example relate to sizing (how much or how many material(s) should be processed and stored), assignment (where and what material should be processed and stored), sequencing (which succession of operations to produce materials should be followed by production) and timing (when should material be processed). These decisions are dependent on information that can be static or dynamic. Static information corresponds to the fixed characteristics or attributes of the production system that can be called “model data”, such as equipment capacities, connectivity and compatibility. Dynamic information is a group of characteristics that may change during the planning/ scheduling horizon or cycle. For this reason, this information can also be called “cycle data”, since it may vary within (or between) decision-making horizons (Kelly, 2005a, 2005b). Note that within a time horizon there may be several cycles. As an example of cycle data, there can be several supply- and/or demand orders of the same feed-stock with many different arrival or departure times during the horizon.

3.1. Model Data

Model data expresses the general behavior of the decision-making problem, and does not change from one decision-making horizon to the next. It encompasses information on the physical elements of the system, as well as the procedural aspects. Model data also contains the physical and procedural connectivity between system elements. It is important to note that information regarding material compatibilities, as well as numeric data relating to equipment sizes, upper and lower bounds on processing capacities, etc., are all included as part of model data.

3.2. Cycle Data

Cycle data is comprised of two main elements: openings and orders. Openings establish the start of the horizon. It is comprised not only of quantity and quality data (such as the amount and composition of material in the tanks) but also logic data in terms of the logic status of equipment (e.g., which service mode the tanks are in) as well as the past and present start times of tasks which are still being performed at the start of the horizon. An order is part of cycle data. It is a temporal requirement that is to be executed sometime in the future. The importance of orders in APS systems is three-fold: (1) orders enable the integration of diverse decision-making layers of an enterprise, (2) orders aid in increasing the transparency of the model as well as the ownership of the solution by the users and (3) orders may improve the solution performance of APS problems by restricting the feasible region of the optimization by allowing certain binary variables to be fixed for example. Different types of orders may be routinely used and can be found in Kelly and Zyngier (2008).

3.3. Objective/ Goal Data

There are several types objectives in decision-making problems in manufacturing, which are largely dependent on the system in question and the scope of the problem. Obviously the choice of objective function has a direct impact on the computational
performance of the decision-making problem. Some objectives may also be quite difficult to implement for a given system representation even requiring additional variables and constraints (Mendez et al. 2006). A few of the frequently used objectives in APS systems are: (1) profit-related such as maximizing the flow of products, or maximizing the net present value on a return of investment; (2) cost-related objectives, such as minimizing the use of raw materials, energy and/or utilities; (3) Inventory-related objectives such as minimizing inventory or holding costs; (4) Timing-related objectives such as earliness, tardiness, makespan. More recently, sustainability criteria have also been included in the design of supply chains, in a field called "Green Supply Chain Management" (Grossmann & Guillén-Gosálbez, 2010).

4. Conclusions
This paper presents a new concept for modeling the details of APS problems for many manufacturing systems. A general architecture is proposed which minimizes the need to modify the underlying model at each decision-making cycle. UOPSS is a very efficient structure and has been applied successfully in practice covering a broad range of industrial sectors, including (but not limited to) mining, steel, oil & gas, refining, pharmaceuticals and food and beverage.

References
J.D. Kelly, 2005a, Modeling Production-Chain Information. CEP (February), p.28-31.
J.D. Kelly, 2005b, The Unit-Operation-Stock Superstructure (UOSS) and the Quantity-Logic-Quality Paradigm (QLQP) for Production Scheduling in the Process Industries, In G. Kendall, L. Lei, & M. Pinedo, eds. Proceedings of MISTA2005. NY, USA, p.327-333.