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Production Scheduling of Supply Chains Comprised of Modular Production Units

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Abstract: In this work, we introduce a mixed-integer linear programming (MILP) formulation to determine the optimal production schedule of a supply chain network with production facilities comprised of transportable modular production units. The problem is solved in a rolling horizon fashion, which allows for rapid changes in raw material availabilities and product demands. The effectiveness of our methodology is illustrated through the use of a circular supply chain case study. The case study is centered in the Permian Basin and focuses on a set of wastewater treatment facilities comprised of modular processing units. The results illustrate the benefits of utilizing production facilities comprised of modular production units operating in parallel, wastewater storage units, and fresh water storage units.

Keywords: Industrial applications of process control, Control and optimization of supply chains

1. INTRODUCTION

Traditionally, industry has relied upon an "economies of scale" approach for the construction of production facilities Arora et al. (2020). Recently, there has been a push towards circular supply chains focusing on waste reductions, Avraamidou et al. (2020), and decentralized supply chains with production facilities comprised of modular production units that can rapidly be reallocated between facilities to meet changes in feed stock availabilities and product demands Baldea et al. (2017).

A key component in the design and operation of supply chains comprised of modular production units is the determination of the optimal allocation of the modular production units. Within the process systems engineering community, Tan and Barton (2015), were the first to formally address the allocation problem. Shortly thereafter, Gao and You (2017), illustrated the benefits of modular production units in a shale gas field; Allen et al. (2018), put forth a multi-stage stochastic MILP formulation for determining the optimal allocation of modular production units given uncertain feed stock availabilities; and Chen and Grossmann (2019), put forth a generalized disjunctive approach to illustrate the benefits of utilizing decentralized modular production units as opposed to centralized large-scale production. More recently, Allman and Zhang (2020), presented a method to decompose large scale allocation problems through the use of "branch-and-price". However, to the authors knowledge there has been no work specifically focusing on real-time operational scheduling of decentralized supply chains comprised of modular production units.

Therefore, in this work we present a framework to determine in real-time the optimal production schedule of a decentralized supply chain network comprised of modular production units. The decentralized network includes: (i) raw material sources that can be routed to raw material sinks or to production facilities, (ii) production facilities, which are comprised of transportable modular production units operating in parallel, backlog raw material storage units, and surplus product storage units, and (iii) sinks whose product demands can be met by the production facilities or external product sources. The objective is to minimize the operational cost of the network.

The major contributions of this paper are as follows: (i) we introduce a MILP formulation to determine the optimal real-time production schedule of a supply chain network comprised of transportable modular production units that is solved in a rolling horizon framework, (ii) we illustrate the benefits of incorporating raw material backlog and product surplus storage units at the production facilities, and (iii) we preform computational studies on a data set for an unnamed waste water treatment company operating in the Permian Basin, who treats produced water from oil and gas wells and supplies the treated water to fracking companies.

2. PROBLEM STATEMENT

Consider a supply chain network and a time horizon, $\mathcal{T} \triangleq \{k, k+1, \ldots, k+|\mathcal{T}|-1\}$, where planning decisions can be made, such that k is the current iteration in the rolling horizon framework. The supply chain network includes raw materials sources, $\mathcal{A}$, production facilities, $\mathcal{F}$, comprised of modular production units, $\mathcal{S}$, product demand sinks, $\mathcal{B}$, raw material sinks, $\mathcal{C}$, external product sources, $\mathcal{D}$, and a transportation network that allows raw material and products to be transferred within the supply chain network. Raw material can be transported from the source locations to production facilities, where the production facilities transform the raw material into products, or to the excess raw material sinks. It should be highlighted, that we allow for excess raw material sinks for the cases when the effluent from the raw material sources is greater than the combined production capacity of all the modular units and the backlog storage capacity or when there is a lack of product demands. The products created at the production facilities are then transported to the demand sinks. The demand of the sinks can also be fulfilled by product sources. The superstructure of this supply chain network is given in Fig. 1.

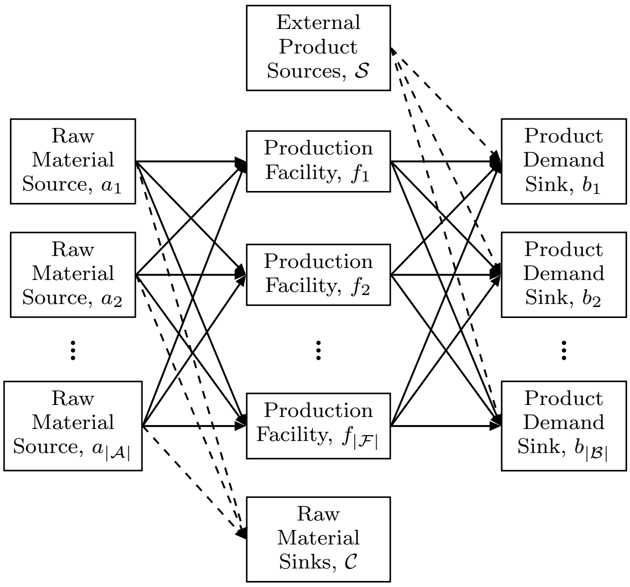

Fig. 1. Superstructure of the Supply Chain Network

The amount of raw material for each source that must either be transported to the production facilities or disposed of at the raw material sinks for every time period is given by, $\mathrm{P}_{t,a}^{\mathrm{material\_supply}}$, where $t \in \mathcal{T}$ and $a \in \mathcal{A}$. The time invariant upper bound on the amount of material that can be routed from a raw material source to a production facility is given by $\mathrm{P}_{a,f}^{\mathrm{material\_capacity}}$, where $a \in \mathcal{A}$ and $f \in \mathcal{F}$. It is assumed that there is no upper bound on the amount of raw material that can be transferred to the raw material sinks and raw material can only be routed form one raw material source to one raw material sink.

The amount of product that must be transported to each demand sink from either the production facilities or the external product sources for every time period is given by, $\mathrm{P}_{t,b}^{\mathrm{product\_demand}}$, where $t \in \mathcal{T}$ and $b \in \mathcal{B}$. There is a time invariant upper bound on the amount of products that can transported from the production facilities to the demand sinks that is represented by the parameter $\mathrm{P}_{f,b}^{\mathrm{product\_capacity}}$, where $f \in \mathcal{F}$ and $b \in \mathcal{B}$. It is assumed that there is no upper bound on the amount of products that can be purchased from the product sources to meet the demand requirements and product can only be purchased from one external product source for each of the product demand sinks.

The production facilities are comprised of modular production units operating in parallel with fixed capacities, a backlog storage unit, and a surplus storage unit. The maximum production capacity of the facility is the combined production capacity of all the modular units, $s \in \mathcal{S}$, that are located at that facility. The modular production units, $s \in \mathcal{S}$, can be reallocated between production facilities at discretized points in the time horizon, $t \in \mathcal{T}$ and have a fixed maximum production capacity, $\mathrm{P}_{s}^{\mathrm{capacity}}$.

When the material enters into the production facility it is either routed to the modular production units or to the backlog storage unit, where it is stored to be processed at a later time. The initial and maximum capacity of the backlog storage unit is given by $\mathrm{P}_{f}^{\mathrm{initial\_backlog}}$ and $\mathrm{P}_{f}^{\mathrm{backlog\_capacity}}$ respectively, where $f \in \mathcal{F}$. When the product leaves the modular production units it is either routed to the demand sinks or to the surplus storage unit, where it can be stockpiled to be sent to the demand sinks at a later time. The initial and maximum capacity of the surplus storage unit is given by $\mathrm{P}_{f}^{\mathrm{initial\_surplus}}$ and $\mathrm{P}_{f}^{\mathrm{surplus\_capacity}}$ respectively, where $f \in \mathcal{F}$. The superstructure of a production facility is given in Fig. 2.

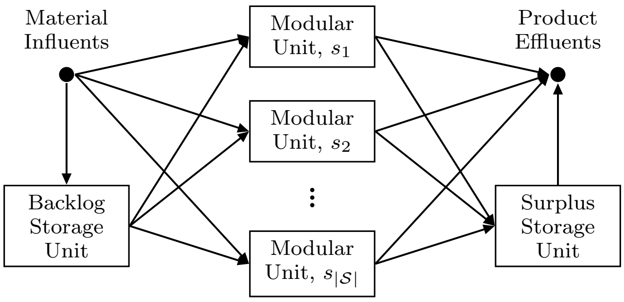

Fig. 2. Superstructure of a Production Facility

The decisions variables of the problem are as follows: (i) the amount of raw material that is transported to the raw material sinks and to each processing facility; (ii) the amount of raw material routed to the backlog storage unit and modular processing units for each facility; (iii) the amount of product produced at each modular unit and if it is operational or nonoperational; (iv) the amount of product that is routed to the surplus storage unit and the demand sinks; (v) the amount of product produced at the processing facilities and stockpiled in the surplus storage units is transported to each demand source; (vi) the amount of product that is purchased from the product sources for each demand sink; and (vii) how the modular processing units are reallocated between the processing facilities, occurring at every time period in the time horizon.

The objective is to minimize the cost of the aforementioned decisions. We assume that there is perfect information regarding raw material availabilities and product demands. The production scheduling problem is then resolved as new information becomes available.

3. PROBLEM FORMULATION

3.1 MILP Formulation

The MILP formulation of the problem is given by (1).

$$\begin{array}{ll} \min & J_1 + J_2 + J_3 + J_4 + J_5 + J_6 \\ \text{s.t} & \text{Eqs. } (1-16) \end{array} \tag{1}$$

3.2 Objective Functions

As mentioned before, the objective is to minimize the operational cost of the network.

Equation (2) sums the fixed, $\mathrm{F}^{\text{material\_flow}}_{a,f}$, and variable, $\mathrm{V}^{\text{material\_flow}}_{a,f}$, cost respectively to transport the raw material from the sources, $a \in \mathcal{A}$ to the production facilities, $f \in \mathcal{F}$.

$$J_1 \triangleq \sum_{t\in\mathcal{T}} \sum_{a\in\mathcal{A}} \sum_{f\in\mathcal{F}} \Big(\mathrm{F}^{\text{material\_flow}}_{a,f} \cdot y^{\text{material\_flow}}_{t,a,f} \dots + \mathrm{V}^{\text{material\_flow}}_{a,f} \cdot x^{\text{material\_flow}}_{t,a,f} \Big) \tag{2}$$

The binary variable, $y^{\text{material\_flow}}_{t,a,f}$, is equal to one if raw material is routed from a raw material source, $a \in \mathcal{A}$, to a facility, $f \in \mathcal{F}$, during a time period, $t \in \mathcal{T}$; otherwise, it is equal to zero. The non-negative continuous variable, $x^{\text{material\_flow}}_{t,a,f}$, indicates the quantity of raw material routed from a raw material source, $a \in \mathcal{A}$, to a facility, $f \in \mathcal{F}$, during a time period, $t \in \mathcal{T}$.

Equation (3) sums the fixed, $\mathrm{F}^{\text{material}}_{a}$, and variable, $\mathrm{V}^{\text{material}}_{a}$, cost respectively to transport and dispose of raw material, $a \in \mathcal{A}$, to the excess raw material sinks.

$$J_2 \triangleq \sum_{a\in\mathcal{A}} \sum_{f\in\mathcal{F}} \Big(\mathrm{F}^{\text{material}}_{a} \cdot y^{\text{excess\_material}}_{t,a} \dots + \mathrm{V}^{\text{material}}_{a} \cdot x^{\text{excess\_material}}_{t,a} \Big) \tag{3}$$

The binary variable, $y^{\text{excess\_material}}_{t,a}$, is equal to one if raw material is routed from a raw material source, $a \in \mathcal{A}$, to a raw material sink during a time period, $t \in \mathcal{T}$; otherwise, it is equal to zero. The non-negative continuous variable, $x^{\text{excess\_material}}_{t,a}$, indicates the quantity of raw material routed from a raw material source, $a \in \mathcal{A}$, to a raw material sink during a time period, $t \in \mathcal{T}$.

Equation (4) sums the fixed, $\mathrm{F}^{\text{operation}}_{s}$, and variable, $\mathrm{V}^{\text{operation}}_{s}$, cost respectively for the operation of the modular production units, $s \in \mathcal{S}$.

$$J_3 \triangleq \sum_{s\in\mathcal{S}} \sum_{(i,j)\in\mathcal{E}_s} \Big(\mathrm{F}^{\text{operation}}_{s} \cdot y^{\text{operation}}_{s,i,j} \dots + \mathrm{V}^{\text{operation}}_{s} \cdot x^{\text{operation}}_{s,i,j} \Big) \tag{4}$$

The binary variable, $y^{\text{operation}}_{s,i,j}$ is equal to one if the modular unit, $s \in \mathcal{S}$, is operational at the facility and time period corresponding to the edge (i,j), such that $(i,j) \in \mathcal{E}_s$, where $\mathcal{E}_s$, is a set of edges that spatially and temporally track the modular unit, $\in \mathcal{S}$; otherwise, it is equal zero. The non-negative continuous variable, $x^{\text{operation}}_{s,i,j}$, indicates the operating set of the modular unit, $s \in \mathcal{S}$, at the facility and time period corresponding to the edge (i,j), such that $(i,j) \in \mathcal{E}_s$.

Equation (5) sums the transportation cost, $\mathrm{F}^{\text{location}}_{s,i,j}$, to relocate the modular production units, $s \in \mathcal{S}$, the supply chain.

$$J_4 \triangleq \sum_{s\in\mathcal{S}} \sum_{(i,j)\in\mathcal{E}_s} \mathrm{F}^{\text{location}}_{s,i,j} \cdot y^{\text{location}}_{s,i,j} \tag{5}$$

The binary variable $y^{\text{location}}_{s,i,j}$ indicates if a modular production unit, $s \in \mathcal{S}$, traverses the edge $(i,j) \in \mathcal{E}_s$. Practically, $y^{\text{location}}_{s,i,j}$, spatially and temporally tracks the modular unit, $\in \mathcal{S}$, in the supply chain.

Equation (6) sums the fixed and variable cost, $\mathrm{F}^{\text{product\_flow}}_{f,b}$ and $\mathrm{V}^{\text{product\_flow}}_{f,b}$, to transport product from the facilities, $f \in \mathcal{F}$, to the demand sinks, $b \in \mathcal{B}$.

$$J_5 \triangleq \sum_{t\in\mathcal{T}} \sum_{f\in\mathcal{F}} \sum_{b\in\mathcal{B}} \Big(\mathrm{F}^{\text{product\_flow}}_{f,b} \cdot y^{\text{product\_flow}}_{t,f,b} \dots + \mathrm{V}^{\text{product\_flow}}_{f,b} \cdot x^{\text{product\_flow}}_{t,f,b} \Big) \tag{6}$$

The binary variable, $y^{\text{product\_flow}}_{t,f,b}$, is equal to one if product is routed from a production facility, $f \in \mathcal{F}$, to a product demand sink, $b \in \mathcal{B}$, during a time period, $t \in \mathcal{T}$; otherwise, it is equal to zero. The non-negative continuous variable, $x^{\text{product\_flow}}_{t,f,b}$, indicates the quantity product routed from a production facility, $f \in \mathcal{F}$, to a product demand sink, $b \in \mathcal{B}$, during a time period, $t \in \mathcal{T}$.

Equation (7) sums the fixed, $\mathrm{F}^{\text{product}}_{b}$, and variable, $\mathrm{V}^{\text{product}}_{b}$, cost respectively to purchase and transport the product from the external product sources to the demand sinks, $b \in \mathcal{B}$.

$$J_6 \triangleq \sum_{t\in\mathcal{T}} \sum_{b\in\mathcal{B}} \Big(\mathrm{F}^{\text{product}}_{b} \cdot y^{\text{product\_purchased}}_{t,b} \dots + \mathrm{V}^{\text{product}}_{b} \cdot x^{\text{product\_purchased}}_{t,b} \Big) \tag{7}$$

The binary variable, $y^{\text{product\_purchased}}_{t,b}$, is equal to one if product is purchased from an external product source and routed to a product demand sink, $b \in \mathcal{B}$, during a time period, $t \in \mathcal{T}$; otherwise, it is equal to zero. The non-negative continuous variable, $x^{\text{product\_purchased}}_{t,b}$, indicates the quantity of product purchased from an external product source and routed to a product demand sink, $b \in \mathcal{B}$, during a time period, $t \in \mathcal{T}$.

3.3 Network Flow Constraints

The backbone of the problem formulation is the modular production unit allocation graph, $\mathcal{G}$, which can be seen in Fig. 3.

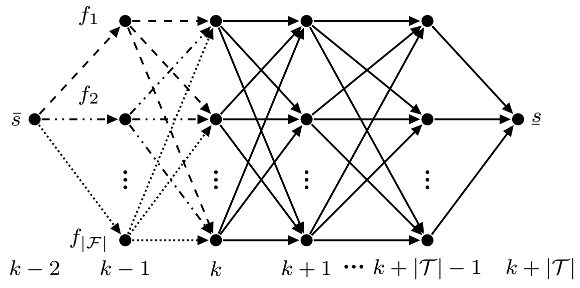

Fig. 3. Graph for the Allocation of a Modular Unit

The nodes in the graph, $\mathcal{G}$, are given as $\mathcal{N} \triangleq \{\bar{s}\} \cup (\{k-1, k, \dots, k+|\mathcal{T}|-1\} \times \mathcal{F}) \cup \{\underline{s}\}$, where $\bar{s}$ is a dummy source node, and $\underline{s}$ is a dummy sink node. The edges in the graph, $\mathcal{G}$, illustrate how the modular units, $s \in \mathcal{S}$ can be reallocated to different facility or remain at the same facility in the supply chain and are given as $\mathcal{E} \subset \{\mathcal{N} \times \mathcal{N}\}$.

For each modular production unit, $s \in \mathcal{S}$, we define $\mathcal{E}_s \triangleq \{(i,j) \in \mathcal{E} \mid \phi_{s,i,j} = 1\}$, where $\phi_{s,i,j}$ is a parameter that is equal to one if there is an edge from node i to node j in the set of edges, $\mathcal{E}$, for a modular unit, $s \in \mathcal{S}$; otherwise, it is equal to zero. It should be noted that this approach allows for varying the transportation time of a modular unit between different combinations of facilities. It also allows the problem to be resolved while the modular unit is in transit, and therefore, reroute a modular unit while it is in transit.

Similarly, for each modular production unit, $s \in \mathcal{S}$, let, $\mathcal{N}_s \triangleq \{k \mid (i,j) \in \mathcal{E}_s, k \in \{i,j\}\}$, $\mathcal{N}^-_{s,j} \triangleq \{i \mid (i,j) \in \mathcal{E}_s\}$, and $\mathcal{N}^+_{s,i} \triangleq \{j \mid (i,j) \in \mathcal{E}_s\}$.

Equation (8) allows the location of a modular unit, $s \in \mathcal{S}$, to be spatially tracked through the scheduling horizon.

$$\sum_{i \in \mathcal{N}^-_{s,j}} y^{\text{location}}_{s,i,j} = \sum_{k \in \mathcal{N}^+_{s,j}} y^{\text{location}}_{s,j,k} \; \forall s \in \mathcal{S}, j \in \mathcal{N}_s \quad (8)$$

3.4 Production Constraints

Equation (9) is a material balance for each raw material source and ensures that the raw material is either routed to a production facility or to a excess raw material sink.

$$\begin{aligned} &\mathrm{P}^{\text{material\_supply}}_{t,a} = x^{\text{excess\_material}}_{t,a} \dots \\ &+ \sum_{f \in \mathcal{F}} x^{\text{material\_flow}}_{t,a,f} \; \forall t \in \mathcal{T}, a \in \mathcal{A} \end{aligned} \quad (9)$$

Equation (10) is a raw material balance for the facilities and ensures that the raw material routed to the facility is either processed or stored in the backlog storage units.

$$\begin{aligned} &\sum_{a \in \mathcal{A}} x^{\text{material\_flow}}_{t,a,f} = x^{\text{production}}_{t,f} + x^{\text{backlog\_material}}_{t,f} \dots \\ &- x^{\text{backlog\_material}}_{t-1,f} \; \forall t \in \mathcal{T}, f \in \mathcal{F} \end{aligned} \quad (10)$$

Equation (11) ensures the product produced at the facility, $f \in \mathcal{F}$, during time period, $t \in \mathcal{T}$, is equal to the operational set point of all of the modular units located at that facility.

$$x^{\text{production}}_{t,f} = \sum_{s \in \mathcal{S}} \sum_{(i,j) \in \mathcal{E}_{s,t,f}} x^{\text{operation}}_{s,i,j} \; \forall t \in \mathcal{T}, f \in \mathcal{F} \quad (11)$$

It should be noted that the edges $\mathcal{E}_{s,t,f}$ is a subset of the edges $\mathcal{E}_s$ and correspond to the edges incident to a facility, $f \in \mathcal{F}$, and a time period, $t \in \mathcal{T}$.

Equation (12) is a product balance for the facilities and ensures that the product produced is either routed to a demand sink or stored in the surplus storage units to be utilized at a later time.

$$\begin{aligned} &\sum_{b \in \mathcal{B}} x^{\text{product\_flow}}_{t,f,b} = x^{\text{production}}_{t,f} - x^{\text{surplus\_product}}_{t,f} \dots \\ &+ x^{\text{surplus\_product}}_{t-1,f} \; \forall t \in \mathcal{T}, f \in \mathcal{F} \end{aligned} \quad (12)$$

Equation (13) is a product balance at the demand sinks and ensures that the product demands are met through either product produced at the production facilities or purchased from the surplus storage unit.

$$\begin{aligned} &\mathrm{P}^{\text{product\_demand}}_{t,b} = x^{\text{product\_purchased}}_{t,b} \dots \\ &+ \sum_{f \in \mathcal{F}} x^{\text{product\_flow}}_{t,f,b} \; \forall t \in \mathcal{T}, b \in \mathcal{B} \end{aligned} \quad (13)$$

Equation (14) ensures that a modular unit can only operate at a facility if located there.

$$y^{\text{operation}}_{s,i,j} \le y^{\text{location}}_{s,i,j} \; \forall s \in \mathcal{S}, (i,j) \in \mathcal{E}_s \quad (14)$$

Equation (15) ensures that the operational set point of a modular unit, $s \in \mathcal{S}$ is less than its maximum capacity, $\mathrm{P}^{\text{capacity}}_s$.

$$x^{\text{operation}}_{s,i,j} \le \mathrm{P}^{\text{capacity}}_s \cdot y^{\text{operation}}_{s,i,j} \; \forall s \in \mathcal{S}, (i,j) \in \mathcal{E}_s \quad (15)$$

Equations (16) and (17) enforce an upper bound on the flow of raw material between the raw material sources and facilities and the flow of products between the facilities and the demand sinks respectively.

$$\begin{aligned} &x^{\text{material\_flow}}_{t,a,f} \le \mathrm{P}^{\text{material\_capacity}}_{a,f} \cdot y^{\text{material\_flow}}_{t,a,f} \dots \\ &\forall t \in \mathcal{T}, a \in \mathcal{A}, f \in \mathcal{F} \end{aligned} \quad (16)$$

$$\begin{aligned} &x^{\text{product\_flow}}_{t,f,b} \le \mathrm{P}^{\text{product\_capacity}}_{f,b} \cdot y^{\text{product\_flow}}_{t,f,b} \dots \\ &\forall t \in \mathcal{T}, f \in \mathcal{F}, b \in \mathcal{B} \end{aligned} \quad (17)$$

Equations (18) and (19) enforce an upper bound on the amount of excess raw material routed to the raw material sinks and the amount of product purchased respectively.

$$\begin{aligned} &x^{\text{excess\_material}}_{t,a} \le \mathrm{P}^{\text{material\_supply}}_{t,a} \dots \\ &\cdot y^{\text{excess\_material}}_{t,a} \forall t \in \mathcal{T}, a \in \mathcal{A} \end{aligned} \quad (18)$$

$$\begin{aligned} &x^{\text{product\_purchased}}_{t,b} \le \mathrm{P}^{\text{product\_demand}}_{t,b} \dots \\ &\cdot y^{\text{product\_purchased}}_{t,b} \; \forall t \in \mathcal{T}, b \in \mathcal{B} \end{aligned} \quad (19)$$

Equations (20) and (21) enforce an upper bound on the storage capacity of storage units located at facilities.

$$x^{\text{backlog\_material}}_{t,f} \le \mathrm{P}^{\text{backlog\_capacity}}_f \; \forall t \in \mathcal{T}, f \in \mathcal{F} \quad (20)$$

$$x^{\text{surplus\_product}}_{t,f} \le \mathrm{P}^{\text{surplus\_capacity}}_f \; \forall t \in \mathcal{T}, f \in \mathcal{F} \quad (21)$$

Equations (22) and (23) enforce the initial capacity of the storage units located at the facilities.

$$x^{\text{backlog\_material}}_{t,f} = \mathrm{P}^{\text{initial\_backlog}}_f \; \forall t \in \{0\}, f \in \mathcal{F} \quad (22)$$

$$x^{\text{surplus\_product}}_{t,f} = \mathrm{P}^{\text{initial\_surplus}}_f \; \forall t \in \{0\}, f \in \mathcal{F} \quad (23)$$

4. CASE STUDY

We utilize a case study focusing on an unnamed wastewater treatment company operating in the Permain Basin.

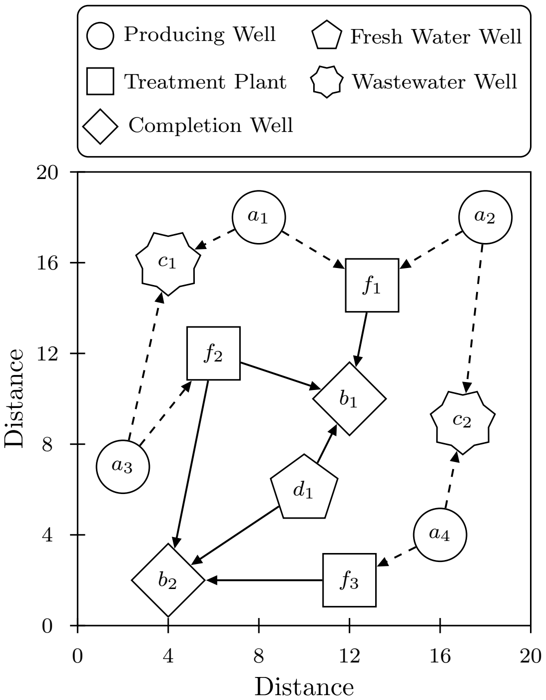

Fig. 4. Superstructure of the Water Treatment Network

The business objectives of the wastewater treatment company is to treat the wastewater effluents from producing oil and gas wells, so that the treated water can then be reused in the completion phase of wells that are currently undergoing fracking. Therefore, we formulate a purely economic objective function for the optimization problem, (1), that is solved in a rolling horizon fashion.

The data set we have been given includes wastewater effluent flow rates from the producing wells and water demands for wells undergoing completion that require fresh water for fracking. We utilize a subset of this data set to illustrate the effectiveness of the proposed production scheduling for a circular supply chain network comprised of modular production units.

The superstructure of the water treatment network is given in Fig. 4. For this case study: (i) the raw material sources, $a \in \mathcal{A}$, are producing oil and gas wells whose effluents contain large amounts of wastewater, (ii) the product sources, $b \in \mathcal{B}$, are wells that are undergoing completion and require water for fracking, (iii) the production facilities, $f \in \mathcal{F}$, are water treatment facilities that treat the wastewater from the producing wells, (iv) the modular production units, $s \in \mathcal{S}$, are modular wastewater treatment units and are mounted on the back of semi-trailers, (v) the raw material sinks, $c \in \mathcal{C}$, are wastewater disposal wells that inject the wastewater into underground reservoirs, (vi) the product sources, $d \in \mathcal{D}$, are water wells that are able to supply the wells undergoing completion with fresh water in the case that the production facilities cannot meet the water demands or they are no longer economical, and (vii) the transportation mechanism that moves wastewater and fresh water through the system is a pipeline network.

5. RESULTS AND DISCUSSION

5.1 Implementation

The algebraic model of the MILP production scheduling problem was implemented in Julia 1.1.0 utilizing JuMP 0.19.2 and solved via Gurobi 8.1.1 Bezanson et al. (2017); Dunning et al. (2017); Gurobi Optimization, LLC (2019). The computation studies were implemented on a machine with a 2.8 GHz Intel Core i7 processor and 16 GB of RAM.

To increase the computational speed of the rolling horizon problem, the problem was warm started by utilizing the previous iterations integer solution Gurobi Optimization, LLC (2019).

The compiled model consists of 8,561 continuous variables, 11,366 binary variables and 29,728 constraints, and was complied and solved in 36 seconds to an optimality gap of approximately 0.1%. The extremely short computational time is due in large part to the warm start.

5.2 Results

As we mentioned before, we utilize a data set that includes the wastewater effluent flow rates from producing wells and water demands for wells undergoing completion. We solve the optimization problem, (1), utilizing a subset of this data in a rolling horizon fashion. The scheduling horizon for the optimization problem, (1), is taken to be 144 time periods in length and each time period corresponds to one hour. We illustrate the solution of the optimization problem, (1), at the k iteration of the rolling horizon framework, which is taken to be the start of the third week of the data set.

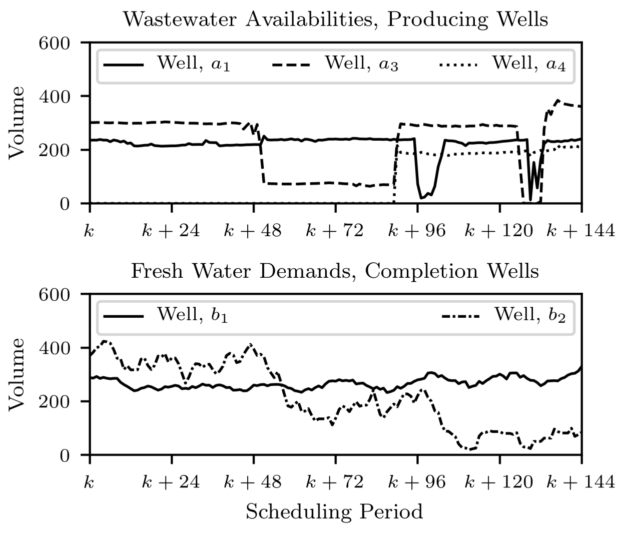

Fig. 5. Wastewater Availabilities and Fresh Water Demands for Producing Wells and Wells Undergoing Completion Respectively

Figure 5 illustrates the wastewater availabilities for the 4 producing wells and the fresh water demands for the 2 wells undergoing completion, whose locations are given in Fig. 4. It should be highlighted that at the second well, a_2, as seen Fig. 4, has not begun producing when this iteration is solved and therefore it is not shown in Fig. 5.

Figure 6 illustrates the production capacity, operating production level as well as the capacity of the backlog wastewater and surplus fresh water storage tanks for facilities 1, f_1, and 3, f_3, respectively. It should be highlighted that these two facilities where chosen for illustration because a modular unit was transferred from facility 1, f_1, to facility 3, f_3, at the $k + 75$ scheduling period.

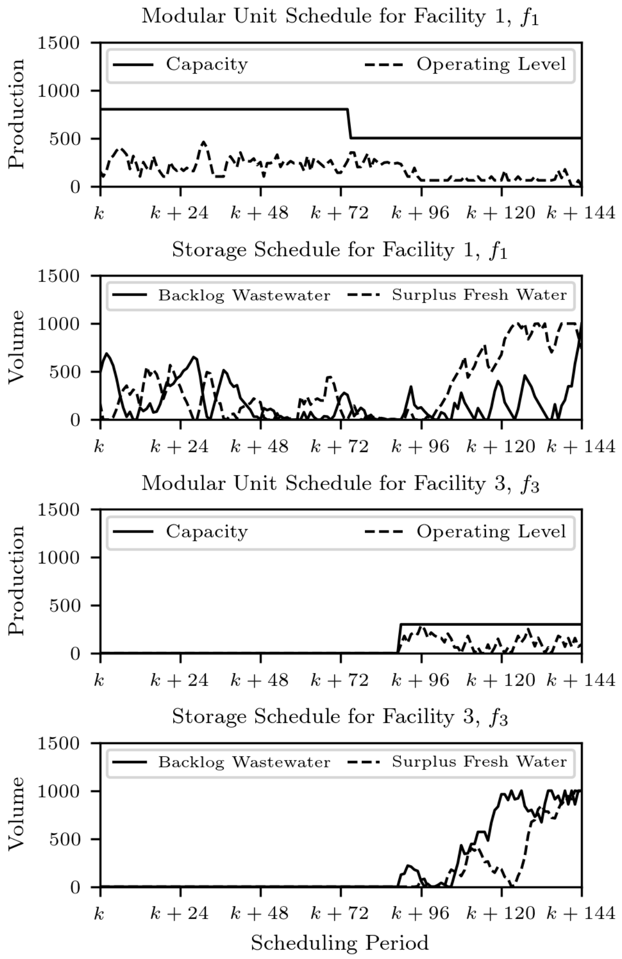

Fig. 6. Operational Schedules for Production Facilities 1, f_1, and 3, f_3, Respectively

From the simultaneous inspection of Fig. 5 and Fig. 6 it can be seen that the backlog wastewater and surplus fresh water storage tanks fluctuate in accordance to the small perturbations in raw material availabilities and product demands.

6. CONCLUSION

We have introduced a MILP formulation to determine the optimal production scheduling of supply chains comprised of transportable modular production units, which we have embedded into a rolling horizon framework. We illustrate the effectiveness of our methodology through the use of a case study centering around a wastewater treatment company operating in the Permain Basin.

We have shown that utilizing transportable modular production units allows a supply chain network to rapidly adapt to dramatic changes in raw material availabilities and product demands. We have also shown that intermediate raw material and product storage units located in the middle of the supply chain network can reduce the strain on the system brought on by small perturbations in raw material availabilities and product demands.

Determining the optimal operation of supply chains comprised of modular is a challenging problem to solve as the size of the supply chain grow; therefore, a possible future research direction would to develop decomposition methods and or reformulations of the problem.

7. ACKNOWLEDGEMENTS

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