

Bredström, David; Haugen, Kjetil; Olstad, Asmund; Novotný, Jan

Article

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A mixed integer linear programming model applied in barge planning for Omya



David Bredström^a, Kjetil Haugen^{b,*}, Asmund Olstad^b, Jan Novotný^c

^a MIL Innovation AS, Kunnskapspark Molde, Britveien 4, N-6410 Molde, Norway

^b Molde University College, PO Box 2110, N-6402 Molde, Norway

^c Brno University of Technology, Faculty of Mechanical Engineering, Technická 2896/2, 616 69 Brno, Czech Republic

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ABSTRACT

This article presents a mathematical model for barge transport planning on the river Rhine, which is part of a decision support system (DSS) recently taken into use by the Swiss company Omya. The system is operated by Omya's regional office in Cologne, Germany, responsible for distribution planning at the regional distribution center (RDC) in Moerdijk, the Netherlands. The distribution planning is a vital part of supply chain management of Omya's production of Norwegian high quality calcium carbonate slurry, supplied to European paper manufacturers. The DSS operates within a vendor managed inventory (VMI) setting, where the customer inventories are monitored by Omya, who decides upon the refilling days and quantities delivered by barges. The barge planning problem falls into the category of inventory routing problems (IRP) and is further characterized with multiple products, heterogeneous fleet with availability restrictions (the fleet is owned by third party), vehicle compartments, dependency of barge capacity on water-level, multiple customer visits, bounded customer inventories and rolling planning horizon. There are additional modelling details which had to be considered to make it possible to employ the model in practice at a sufficient level of detail. To the best of our knowledge, we have not been able to find similar models covering all these aspects in barge planning. This article presents the developed mixed-integer programming model and discusses practical experience with its solution. Briefly, it also puts the model into the context of the entire business case of value chain optimization in Omya.

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1. Introduction

The barge transport planning in Omya, which is the main focus of this article, is the last stage of a multi-echelon logistic chain [1,2]. We start with a top-down description of the chain, since it gives an important perspective on the barge planning problem.

The Omya calcium carbonate slurry production in Norway consists of about 20 variants that are produced at one single plant, Omya Hustadmarmor (HM), located close to the town Molde on the west coast (refer to Fig. 1). The main raw material for the production of these slurry products is marble stone supplied from one major quarry located in the north of the country (Brønnøy) and some local quarries located close to Molde. The factory has a yearly production of approximately 3 million metric tons.

Omya Hustadmarmor is the biggest of around 120 chemical plants within the Omya company. The calcium carbonate slurry, which is produced here, is used as an add-on to make paper more shiny. The 20 different variants regulate how shiny the paper becomes—from small to high. In general, a higher degree of shininess costs more.

Nearly half of the quantities produced at HM are supplied to German and Dutch paper-mill factories located close to the Rhine and Maas rivers. Serving these customers involves ship transport from HM to the company-owned tank farms (RDCs) located in Emden (Germany) and Moerdijk (Holland)—see Fig. 1.

Each tank farm contains roughly 14 days of demand for allocated customers. The tank farm in Emden, is the biggest, containing around 40 tanks with a total capacity of 60,000 tons of slurry. Normally, around 40,000 tons of this capacity is utilized. If unexpected demand changes occur, a tank allocation system (also a part of the DSS portfolio) is used for tank reallocation.

This transport utilizes 12 heterogeneous chemical tank vessels (ranging from 5000 to 18,000 dwt) owned by Utkilen AS; a Norwegian broker. Serving end customers (the last stage of the multi-echelon transport system) involves river transport by 12

* Corresponding author. Tel.: +47 99456006 (mob); fax: +47 71214100.

E-mail addresses: david@milinnovations.com (D. Bredström), kjetil.haugen@himolde.no (K. Haugen), asmund.olstad@himolde.no (A. Olstad), iannovot@gmail.com (J. Novotný).

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Fig. 1. A sketch of the model geography, including location of plants, tanks and relevant routes.

heterogeneous special-equipped barges (ranging from 800 to 3000 dwt) owned by Wijgula AG (Germany). HM is responsible for the planning of the outbound ship transport and the tank farm management at Moerdijk and Emden, while the office in Cologne is responsible for outbound logistics from the tank farms to end customers involving barge transport. The other half of the produced slurry at HM is supplied to paper-mill factories located in the United Kingdom, Sweden and Finland.

Transportation costs per unit are significantly lower for large ships than for small ships, but their use increases planning complexity and creates problems in production in HM due to limited tank farm capacities.

The production facility in HM consists of production lines that can be switched to production of different variants of the slurry. Switching of production leads to extra costs, given by loss of production capacity due to set-up times and extra (double) production time caused by quality problems. It is not possible to maintain substantial stocks of the finished products at the factory, due to the limited available storage capacities, and also due to quality considerations given by the nature of the products. Production is in this case directly linked to distribution with a short time-lag.

In daily operations the planner at HM has to (1) decide which vessel should depart on which day for which tank farm, and (2) decide what mix of products¹ each vessel should carry. From the above, it should be clear that the main challenges in this planning are to utilize large vessels in the outbound sea transport and produce large production lots with few changeovers between slurries. Product quality aspects, demand variations and tank farm limitations make this planning highly complex. Due to the practical material requirements planning (MRP) logic utilized in the supply chain management of HM/Omya, it is evident that the agent in charge, the logistic department at HM is highly dependent on predictable (reliable) barge plans from the logistic department in Cologne.

Traditionally the Omya logistic planning has been short-termed and so-called “reorder point oriented” where the main actors

in the supply chain management (logistic managers, production planners, different transport operators, RDC managers) typically have spent most of their time communicating and trying to reach agreements on how to handle reorder points and sudden changes caused by delayed vessels, production problems, changed customer orders or other “events” in the value chain.

Throughout the period 2003–2006 the logistic department at HM succeeded in changing their logistic philosophy in sea-transport to a longer term planning system, where demand for different products at different RDCs (e.g. Moerdijk and Emden) was predicted by formal methodologies and safety stocks are calculated based on forecast errors and predefined customer service levels (fill-rates). The forecast and safety stock data are utilized as an input to an advanced ship-planning model that operates on a 4-week rolling planning horizon.

Implementation of the ship-planning model brought total yearly cost savings of about NOK 90 million for the company or about five percent of the company costs. This saving arose from utilization of (much) larger and cost-effective chemical tank vessels in the transportation, substantial improvements in more efficient production planning (reduced number of changeovers in production) and improved maintenance policy. The project also reported positive environmental impacts due to substantial CO₂ and NO_x emission reductions. The ship planning project in HM entered the finals in the 2006 Franz Edelman award. [3].

The ship planning model, as indicated above, provided substantial efficiency improvements. However, its main contribution was related to paper factories within the Scandinavian region where intermodality was not present. On the European mainland, the slurry must be transported (mainly) by barges on European waterways. Hence, in order to achieve similar efficiency improvements on these parts of the value chain, a barge planning system became necessary. The model reported on in this article, solves such a task partly. The obvious answer would be an integrated model involving all parts of the value chain, but model complexity and model size as well as organizational challenges have so far prevented such a full scale optimization implementation. However, the company has realized substantial extra savings, at the same inducing better structural understanding in the organization.

Generally, Omya’s present logistics strategy targets 100% customer delivery service, maximal ship size as well as maximal use of direct transportation (i.e. deliveries to a single plant by each boat).

2. Motivation

The barge planning system for the Omya office in Cologne is a follow-up project of the ship planning system at HM. The main motivation for this project has been to adopt the operations research methodology used in the HM ship planning system to barge planning at Cologne. The tank farm in Moerdijk is the plant where the inbound sea transport and outbound barge transport meet. The transports must be very well synchronized, otherwise stock-out or demurrage can occur. The main idea of the DSS and the barge planning model is to achieve – together with the ship-planning tool – a consistent logistic system based on the following MRP logic:

- (i) First the Omya Cologne office forecast the customer demand and calculate the necessary safety stock at the customer inventories.
- (ii) The calculation under (i) is utilized as input in the presented mathematical model for barge transport planning, operated with a 4 week planning rolling horizon.
- (iii) The output of the barge planning at (ii) is communicated to the logistic department at HM to be utilized as input in the ship planning system as presented in [3] and mentioned above.

¹ That is, what combinations of the 20 variants should be filled into the barge tanks.

(iv) Steps (i)–(iii) will in many situations lead to identifiable suboptimal solutions. Such instances are handled manually through communication between HM and the Omya Cologne office. Obviously, this situation is not ideal, and it has led to a debate on whether to start making a mathematical model which integrates the complete value chain.

Recently Omya has done substantial investments in automatic measurement devices at their tank farms and on customer sites. These investments have accomplished the adoption of the VMI philosophy for logistic planning in the calcium carbonate slurry value chain in Omya.

3. Mathematical model

Barge planning optimization as such, is relatively sparsely treated in OR/Mathematical programming research literature. Some interesting exceptions exist [4,5] perhaps mostly related to simulation. Some more optimization related work [6–8] does exist, although treating slightly different practical situations than ours.

The structural problem under consideration falls into the IRP-category, see e.g. [9,10]. This means that it is itself a combination of a vehicle routing problem [11–13] and an inventory management problem which resembles a lot-sizing problem [14]. The inventory part is modelled as VMI which implies that Omya/HM controls inventory levels at customer sites [1].

The objective is to minimize the total logistic costs, which is a combination of transport costs and inventory holding costs.

Below, we present a linear mixed integer (cf. [15]) formulation of the problem. The model uses discrete time with time-periods indexed by $t^2 \in \{1, \dots, T\}$. The individual customer locations are indexed with $n \in N$ and we alternatively call them nodes. The various products are indexed by $p \in P$ and the individual barges are indexed by $v \in V$. The transportation part of the problem can be characterized as a vehicle routing problem with one central depot and direct deliveries [16]. Omya has in fact requested support of combined transports to selected pairs of destinations. We have tackled this request in the formulation by enumerating the routes. The various routes are indexed by a compound index³ $r = (r_1, r_2) \in N \times (N \cup \emptyset)$. When $r_2 = \emptyset$, r corresponds to a single-destination transport. We implicitly assume that all transports return to the central depot. The travel times are given by the following parameters:

a_{vr}	travel time to the 1st destination—vessel v on route r ,
b_{vr}	travel time to the 2nd destination—vessel v by route r ,
f_{vr}	duration of the whole round-trip—vessel v by route r .

Additionally, the barge capacities also depend on the routes. This is due to various water-levels in the travelled waterways. The draft of the barge (described below) is proportional to its load; the draft (and hence the load) is limited by the minimum water-level along the route. It has been very important to incorporate these parameters into the model, since the water-levels also depend on the weather, and the model should give implementable proposals in all cases. As mentioned previously, the barge fleet is heterogeneous; VRP problems with heterogeneous fleet form their own category within Operations Research, see e.g. [17].

The loading of the barges is a substantially complicated process, restricted by many factors. Each barge has several tanks (compartments), typically 3–6. There can be at most one product loaded to each tank. For a reference on vehicle routing with compartments, see [18]. In practice, the barge operator runs a simulation of the

loading sequence in a specialized software. The simulation proves whether it is possible to load the proposed cargo mix without trimming the barge or damaging its integrity in any way. The real feasibility of the loading depends on the precise loading sequence, on the assignment of products to the individual tanks, on the mutual positions of the tanks within the barge in combination with the proportion of their load, etc. It has not been possible for us to incorporate all these restrictions into the model—such action would imply an integration of the loading-simulation software into our model. Instead, we have adopted the most crucial constraints which have to be satisfied; and this approach turned out to be successful in practice. The constraints are listed below. We index the individual tanks of each barge by $v \in N_v$:

- Each tank v has a maximum volume capacity C_{vv}^V in cubic metres.
- Each tank v has a maximum weight capacity C_{vv}^T in tons.
- The minimum loading and unloading (i.e. delivery) quantity is m tons (typically $m = 200$).
- Each barge v has a maximum total weight limit of \bar{C}_v tons.
- For each barge v and route r , there is an additional weight limit \hat{C}_{vr} implied by the depth of the waterway. The draft of each barge is a function of its weight, and the draft should not exceed the minimal water-level on the route.
- The maximal weight capacity \hat{C}_{vr} of barge v on route r is then given as $\min\{\bar{C}_v, \hat{C}_{vr}\}$.

Since we have to work with both weight and volume limits, we must take into account product densities. The density of product p is denoted by ρ_p .

The aim of the model is to provide a transportation plan—i.e. to assign barges to routes in time periods throughout the planning horizon and to propose the cargo mix. The barge fleet is owned and operated by a third party. Even if the barges have been customarily rebuild and equipped to carry the heavy Omya products, they can be occasionally used for other tasks as well, and they may undergo maintenance. Therefore we have to consider a binary availability parameter A_{vt} .

The main decision variable z_{vrt} indicates that barge v commences route r in time period t . The variable x_{vrpt}^a denotes the amount (in tons) of product p delivered by barge v to the first destination of route r . The variable x_{vrpt}^b denotes the amount delivered to the second destination, and is implicitly zero if r is a single-destination route. The total amount of product p loaded on the barge is then given by $x_{vrpt}^a + x_{vrpt}^b$. The amounts of loaded products are restricted by the barge tanks. Each tank can be allocated to at most one product—the binary variable y_{vtpv} indicates that tank v of barge v is used for product p in the route which the barge undertakes starting in period t . There is at most one such route for each t , so it is sufficient to use the index t instead of r . The minimum loading and unloading quantities are handled with help of binary variables \hat{x}_{vrpt} which indicate whether product p is included in a given transport or not.

In practice, the transportation plan is reviewed day-by-day in a rolling way. The transports which are scheduled in the near future (typically a couple of time periods ahead) are fixed—i.e. they are no further subject to optimization and replanning. There may be some fixed transports also later during the planning period—these are given by specific agreements with the barge operator, customer, etc. The fixed transports and deliveries correspond to fixed values of the variables z_{vrt} , x_{vrpt}^a and x_{vrpt}^b .

We will briefly describe the inventory part of the model. The variables i_{npt} denote the inventory level of product p in node n at time period t . They are governed by the usual inventory-balance equations which incorporate incoming and outgoing quantities. The incoming quantities in node n at time t are given by $x_{vrp,t-a_{vr}}^a$ and $x_{vrp,t-b_{vr}}^b$, where $r = (n, \cdot)$ or $r = (\cdot, n)$, respectively. The

² τ is used as time subscript when necessary if t is “occupied”.

³ In practice, this means that the model tackles up to 2 destinations for each route.

offset in the time index is due to the travel times. Model demand is defined as F_{npt} .

The inventories are bounded from above and from below. The lower limit is given by minimum stock s_{npt} and by zero. In the ideal case, the delivery plan is such that the customer inventories never fall below the pre-set minimum stock. However, this is hard to achieve when the demands are volatile, travel times are subject to delays, etc. It actually turned out to be important (in order to avoid model infeasibilities) to relax even the non-negativity constraint on the stock levels and to run with backlogging.⁴ There is a penalty γ_0 associated with the variable d_{npt}^0 which measures the negative part of i_{npt} . The violation of the minimum stock is measured with the variable d_{npt}^s and the associated penalty is γ_s .

The upper limit on the inventory actually includes a safety margin, which can occasionally be violated in practice. This can occur with the planned fixed deliveries (see above), or with a too high initial measured level. Although the model proposals should respect the upper inventory bound as a hard constraint, the model should be able to withstand these violations. Therefore, we preprocess the upper inventory bound and increase it locally where necessary—resulting in a time-dependent upper bound parameter I_{npt}^{UP} .

The model uses the following index sets:

- \mathcal{P}_n^N For each node n , the set of products which are stored at this node and which can be delivered to this node.
- \mathcal{P}_v^V For each barge v , the set of products that the barge can carry. Some products need to be agitated during the transport, and can only be carried by the subset of barges which are equipped with agitators.
- \mathcal{P}_{rv}^C For each barge v and route r , the set of products that the barge can carry and which can be delivered to the first or second destination of the route. $\mathcal{P}_{rv}^C = \mathcal{P}_v^V \cap (\mathcal{P}_{r_1}^N \cup \mathcal{P}_{r_2}^N)$, where $r = (r_1, r_2)$.
- \mathcal{R}_v For each barge v , the set of routes which the barge can travel. Not all destinations are admissible for each barge due to draft or quay equipment limitations.
- \mathcal{V}_r For each route r , the set of barges which can travel on this route.

The model formulation follows:

$$\begin{aligned} \min \quad & \sum_t \sum_v \sum_{r \in \mathcal{R}_v} c_{vr} z_{vrt} + \sum_t \sum_n \sum_{p \in \mathcal{P}_n} h_{npt} i_{npt} \\ & + \sum_t \sum_n \sum_{p \in \mathcal{P}_n} (\gamma_s d_{npt}^s + \gamma_0 d_{npt}^0) \end{aligned} \quad (1)$$

$$\begin{aligned} \text{s.t.} \quad & i_{np,t} = i_{np,t-1} + \sum_{r: r_1=n} \sum_{v \in \mathcal{V}_r} x_{vrp,t-a_{vr}}^a \\ & + \sum_{r: r_2=n} \sum_{v \in \mathcal{V}_r} x_{vrp,t-b_{vr}}^b - F_{np,t} \quad \forall t \forall n \forall p \in \mathcal{P}_n^N, \end{aligned} \quad (2)$$

$$i_{npt} + d_{npt}^s \geq s_{npt} \quad \forall t \forall n \forall p \in \mathcal{P}_n^N, \quad (3)$$

$$i_{npt} + d_{npt}^0 \geq 0 \quad \forall t \forall n \forall p \in \mathcal{P}_n^N, \quad (4)$$

$$i_{npt} \leq I_{npt}^{UP} \quad \forall t \forall n \forall p \in \mathcal{P}_n^N, \quad (5)$$

$$\sum_{r \in \mathcal{R}_v} \sum_{\tau=t-f_{vr}+1}^t z_{vrt} \leq A_{vt} \quad \forall t \forall v, \quad (6)$$

$$\sum_{p \in \mathcal{P}_{rv}^C} (x_{vrpt}^a + x_{vrpt}^b) \leq \hat{C}_{vr}^T z_{vrt} \quad \forall t \forall v \forall r \in \mathcal{R}_v, \quad (7)$$

$$\sum_{p \in \mathcal{P}_v^V} y_{vtpv} \leq 1 \quad \forall t \forall v \forall v \in \mathcal{N}_v, \quad (8)$$

$$x_{vrpt}^a + x_{vrpt}^b \leq \sum_{v \in \mathcal{N}_v} C_{vv}^T y_{vtpv} \quad \forall t \forall v \forall r \in \mathcal{R}_v \forall p \in \mathcal{P}_{rv}^C, \quad (9)$$

$$\frac{1}{\rho_p} x_{vrpt}^a + \frac{1}{\rho_p} x_{vrpt}^b \leq \sum_{v \in \mathcal{N}_v} C_{vv}^V y_{vtpv} \quad \forall t \forall v \forall r \in \mathcal{R}_v \forall p \in \hat{\mathcal{P}}_{rv}, \quad (10)$$

$$x_{vrpt}^a \leq \hat{x}_{vrpt}^a \hat{C}_{vr}^T \quad \forall t \forall v \forall r \in \mathcal{R}_v \forall p \in \mathcal{P}_{rv}^C, \quad (11)$$

$$x_{vrpt}^a \geq \hat{x}_{vrpt}^a m \quad \forall t \forall v \forall r \in \mathcal{R}_v \forall p \in \mathcal{P}_{rv}^C, \quad (12)$$

$$x_{vrpt}^b \leq \hat{x}_{vrpt}^b \hat{C}_{vr}^T \quad \forall t \forall v \forall r \in \mathcal{R}_v \forall p \in \mathcal{P}_{rv}^C, \quad (13)$$

$$x_{vrpt}^b \geq \hat{x}_{vrpt}^b m \quad \forall t \forall v \forall r \in \mathcal{R}_v \forall p \in \mathcal{P}_{rv}^C, \quad (14)$$

$$i_{np,t} \geq 0, \quad d_{npt}^0 \geq 0, \quad d_{npt}^s \geq 0 \quad \forall t \forall n \forall p \in \mathcal{P}_n^N, \quad (15)$$

$$\begin{aligned} x_{vrpt}^a \geq 0, \quad x_{vrpt}^b \geq 0, \quad \hat{x}_{vrpt}^a \in \{0, 1\}, \quad \hat{x}_{vrpt}^b \in \{0, 1\} \\ \forall t \forall v \forall r \in \mathcal{R}_v \forall p \in \mathcal{P}_{rv}^C, \end{aligned} \quad (16)$$

$$y_{vtpv} \in \{0, 1\} \quad \forall t \forall v \forall v \in \mathcal{P}_v^V \forall v \in \mathcal{N}_v, \quad (17)$$

$$z_{vrt} \in \{0, 1\} \quad \forall t \forall v \forall r \in \mathcal{R}_v. \quad (18)$$

The objective function (1) minimizes the sum of transportation costs (cost for barge v on route r is given by c_{vr}) and inventory-holding costs (cost for one unit of product p at node n in period t is given by h_{npt}). It also contains penalty terms for inventory below minimum stock and zero, as explained above.

Eq. (2) is the inventory balance equation representing the conservation of each product p at each node n . Eqs. (3) and (4) measure the violations of minimum stock and zero at the inventory level. Eq. (5) imposes the preprocessed upper bound on the inventories. Eq. (6) guarantees that each barge is undertaking at most one route at each time period.

Eq. (7) provides the route-dependent weight limit for the transports. Eqs. (8)–(10) handle the allocation of the barge tanks to the products, the first one makes sure that each tank is used for at most one product, the following two represent weight and volume limits of the tanks. Eqs. (11)–(14) take care of the minimum load/delivery quantity logic. For a reference on similar modelling techniques, see [19]. Eqs. (15)–(18) define the domains of the variables.

4. Computational experience

The presented barge planning model, solved with the Coin-OR CBC solver, is being regularly used in planning in the Omya office in Cologne. The model is embedded into the above mentioned decision support system. The users of the DSS interact with the model parameters – demand forecast, inventory capacities, barge master data, etc. – via graphical interfaces. The model solution result – the distribution plan – is also presented in a graphical way.

The computation time is about 5 min to obtain a duality gap estimation of 2%, on a computer with a dual core 2.5 GHz processor. For the size of the data-case, we run with 28 time periods (four weeks, daily), 6 nodes and ca. 20 products with 5 products per node in average. There are 12 barges with 3–6 tanks; most of the barges can visit all locations.

The business case is characterized with tight inventory bounds at some of the destinations. Also, the water-level fluctuations,

⁴ Backlogging was introduced in order to satisfy customer needs even if barge delays occurred.

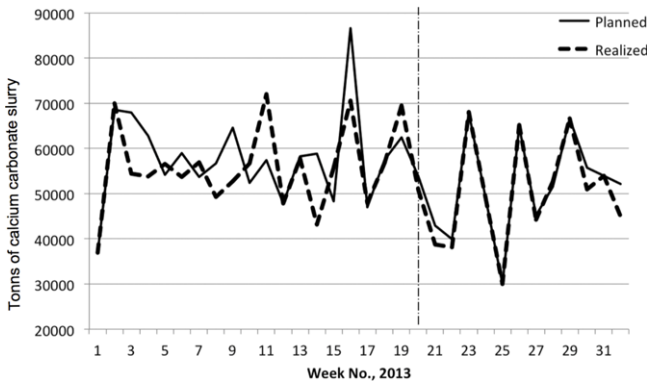


Fig. 2. A comparison of planned and realized outbound transport before and after adopting the planning methodology in week 20, 2013.

which result in temporarily reduced barge capacities, affect the solution substantially.

5. Summary and further research

The mathematical model for barge planning presented in this article has recently been put into operational use as part of a decision support system for barge planning at the Omya office in Cologne. The experience of the DSS so far is improved customer demand forecasts and more precise safety stock calculations. The system has generated quite reliable (stable) long-term barge plans, characterized with less replanning. Longer planning horizons and less replanning for the barges has so far proven to cause more efficient ship planning at HM (less replanning) as illustrated in Fig. 2 below. The figure compares the planned and realized weekly shipments from HM to Moerdijk before and after the first testing period of the barge planning model, which took place in May 2013. After adopting the barge planning model, the company has reported less replanning in the sea transport—as visible in Fig. 2.

In the long run the company expects further improvements in the barge planning (less replanning) which will cause less need for safety stocks at the tank farms in Moerdijk and Emden and thereby increased flexibility in the ship planning.

The DSS for barge transport also provides a tailor-made visualization tool for (i) Gantt chart presentations of barge plans (ii) single or multi-item inventory curves presentations and (iii) demand forecasts and calculated safety stocks presentations. The visualization tool has a multi-user functionality, which opens for communication between different actors (RDCs, transporters and customers) in the Omya value chain slurry production. The tool also has a what-if analysis functionality that allows for consequence evaluations of various events in the value chain—e.g. consequences of barge delays, production stops or increased customer demands on inventory levels at the different RDCs and customer silos.

To show the reader how the DSS may function, Figs. 3 and 4 are presented. Fig. 3 shows a barge plan. Three barges (named Calcit3, –11 and –12) are presented. The length of the grey rectangles (on top in Fig. 3) visualizes barge travel times. The bottom part of Fig. 3 contains inventory consequences for the given barge plan for a single product and a single customer. In order to produce the result in Fig. 4, an operator has identified a delay on barge Calcit12. Now, the operator/user simply drags the grey rectangle of barge Calcit12 in correspondence with the actual delay (as can be observed in Fig. 4). Now, the model recalculates inventory consequences, and stock out is observed (at the bottom of Fig. 4). The mathematical model (defined in the appendix) may be re-executed, fixing Calcit12 to achieve a new feasible solution.

As discussed in the introduction, another important part of the DSS involves optimizing chemical tank vessels transportation from Omya Hustadmarmor to tank farms in Europe. (Moerdijk) This system has a similar GUI, but where barges are replaced by vessels in the Gantt charts. Both models are integrated through so called multi user functionality meaning that inventory curves for different products (slurry qualities) are visible for the common tank farm—at Moerdijk. Omya Hustadmarmor is responsible for filling up these tanks, supplying product input to the barge planning (see Fig. 1). Inventory curves, which are visualized in both systems, react in real-time both in Cologne and in Elnesvågen on changes in barge- or ship plans. For instance, if a delay occurs in some barge on the river Rhine, this is immediately observed at Omya Hustadmarmor in Elnesvågen which may initiate a rerun of the chemical tank vessel optimization model.

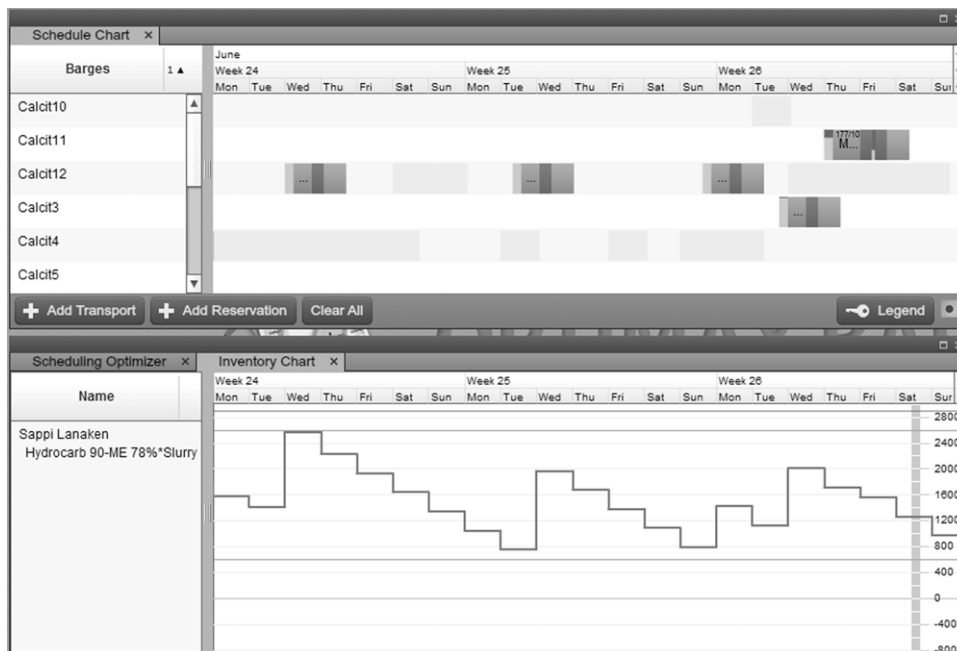


Fig. 3. An example of the visualization tool containing a delivery plan with a Gantt chart in the upper half, and an inventory curve of one selected product in the lower half.

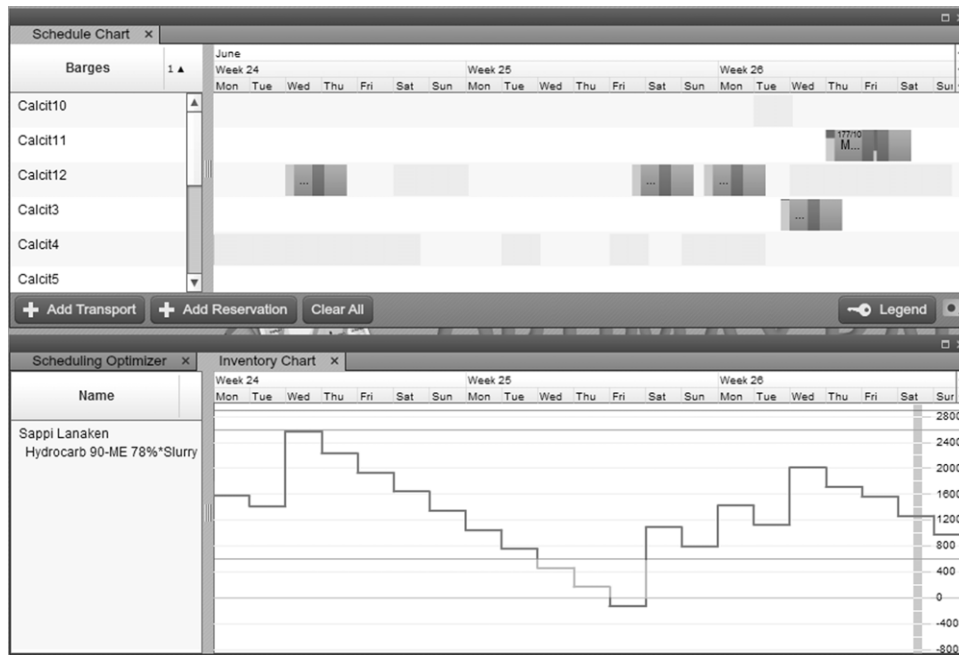


Fig. 4. Another example of the visualization tool describing inventory consequences of a barge delay.

We are fully aware of the fact that the MRP logic in the barge planning system can be further improved by a (more) integrated model for ship and barge planning. This is a topic for further research. Integrated production, lot-sizing and distribution planning might also be topics for further research.

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