

Custom simulator for logistic networks in downstream

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Abstract Performing process simulations is extremely important for the oil industry. One of the fields of application is to schedule and coordinate the supply, distribution, and storage of raw materials, semi-finished, and finished bulk products in a logistics system. A novel simulation method has been introduced here for scheduling the transport of liquids through a pipeline network to ensure the balance among product availability, sales, and transport in each production and distribution point, to display the actual timetable and its effects, and to identify supply–demand imbalances in a model.

Keywords Pipeline · Simulation · Oil industry · Logistic

Introduction

Process simulation has a very important role in the oil refinery industry. Even when all components of a system are well known, i.e., it is clearly defined how a component will react to a specific input, we can only guess how the system as a whole will respond to a particular action. Usually, the system is just too large to understand completely its inner operations. This is usually the consequence of two attributes or their combinations. First, the system has a great number of components, each with plenty of

properties. In this case, there is too much data to keep all of it in mind. Second, the system is highly complex. The input of the system may affect several components; these components affect other components, etc. A single input may cause a ripple effect on the whole system. It is a real possibility that our initial input causes unnecessary side effects or in some cases exactly the opposite of what was originally intended. If a system is both complex and has a great number of building blocks, then it is extremely difficult to predict the reaction for some actions.

A simulator calculates the dynamics of the system, i.e., the future states of the system, for a given input based on the current state and the operations of its components. Moreover, by running different scenarios a simulator helps us to analyze the system, identify bottlenecks, and plan its future operation. It should be always noted that the simulation is only a model of the physical system; consequently, the accuracy of the results depends on the accuracy of the representation.

In a refinery a large number of products are to be produced. The Supply Chain Management (SCM) departments in oil companies are responsible for scheduling and coordinating the supply, the distribution, and the storage of raw materials, semi-finished, and finished bulk products in the logistics system.

MOL Plc is the major Hungarian oil company. In recent years MOL has developed from a national oil company to a regional player in the Central European region. A significant point of MOL strategy is to improve and extend the practical adaptation of the SCM principles to meet the requirements of the growing group. Two of the three main planning pillars of SCM at MOL are the optimization area (planning from 1 month to 10 years or more), and the refinery scheduling area (scheduling the refinery within a month) has been covered by pacesetter applications,

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namely, the PIMS and Orion (Aspentech). Only the third area, the supply and distribution (scheduling the logistics system within the month), has not been supported by any software. Analyzing the scheduling methodology of other players in the industry has indicated that there are no universal pocket solutions; own development, tailored to the logistics system, is typical.

Problem definition

A novel process simulation method was designed and developed to support the scheduling of the logistics system. The simulator is capable of:

- (i) Assisting the design of product pipeline schedule, tank schedule, blending order schedule, and product allocation. Product pipeline schedule defines the circumstances of the transport for each product which contains the transportation time, source, target, and path. The extraction of a tank is the download of its content while the upload of a tank defines its refilling. Blending is the last production step in petro-chemistry. Different additives are mixed to the semi-products to meet product specifications. Blending order schedule is the timetable for the different blending operations. Allocation means the allotment of available products at a given site among transportation types.
- (ii) Tracking the products and raw materials from blending to selling under the supervision of the SCM department, thus, their locations are always known.
- (iii) Ensuring the feasibility of the monthly optimized plan day by day. Monthly optimized plan contains all the activities (blending, uploads, downloads, pipeline transports, etc.) which are timed during the actual month.
- (iv) Simulating and visualizing the transports in the product pipelines in one model.

The proposed system can also be perceived as a decision support tool. Decision making in the oil industry is an outstandingly complex process. Decisions are made at different stages within supply chain distribution and at different levels in the management hierarchy. Decisions also differ in business scope, time horizon, time resolution, data certainty, and process detail. Consequently, there are a high number of factors affecting the decisions. For instance, a relatively small country like Hungary has a complex pipeline structure, shown in Fig. 1. There are two refineries, one petro-chemical site, and more than 10 other sites, where production, storage, and transport between sites have to be carried out for more than 10 product groups (bio gasoline, diesel, heating oil, etc.) which include more than 40

products (e.g., five percent bio ethanol contained 95-MON gasoline, benzene–toluene fraction, virgin naphtha, etc.). The number of pipeline movements ranges between 200 and 250, and the number of blending is between 50 and 70. There are about 3000 domestic sales and about 150 exports in a month.

Nowadays, a large number of oil and chemical companies are still held back by obsolete decision-making processes; see (Lasschuit and Thijssen 2004) and (Cheng and Duran 2004). Decisions and communication across the supply chain are ineffective and delayed, because of off-line erratic spreadsheets, functional barriers between departments, and lack of transparency. All these lead to slow and inept day-to-day decisions that cost companies dearly in terms of financial performance. The legacy way of decision making which is based on spreadsheets, meetings, and phone calls all stand in the way of speed and effectiveness. Consequently, a novel, efficient tool is needed to assist the decisions in supply and distribution scheduling.

The complexity of the problem is raised by pipe-transport planning (movement of intermediates and products), refinery function, sales at every site, and determination of the sequence of products. One of the most important task is the collection of all scheduling information in one simulation to consolidate time horizons (e.g., 4 days long pipe transport plan versus 1 day long allocation plan). Using the simulation the company can move from error-handling to prediction of imbalances and reacting sooner.

Literature review

Modeling, simulation, scheduling, and production planning are major research topics in the oil industry. In this section an outline is to be given about articles related to decision support, process simulation, and product pipeline scheduling.

Vasek and Klemes (1983) has proposed and implemented an early flowsheeting simulation package. The authors have recognized that simulation has a major role in design and proved that significant results can be achieved using the desktop computers of that time.

Crama et al. (2001) has presented an overview about production planning approaches in the process industry. The differences and similarities among different methods have been underlined. Moreover, the distinctive features of the process industry have been presented as they relate to production planning issues. The difficulties encountered with the implementation of classical flow control techniques have been discussed, and various approaches to overcome them have been referenced. A survey of specific flow control models and algorithmic techniques specifically for process industries have also been discussed.

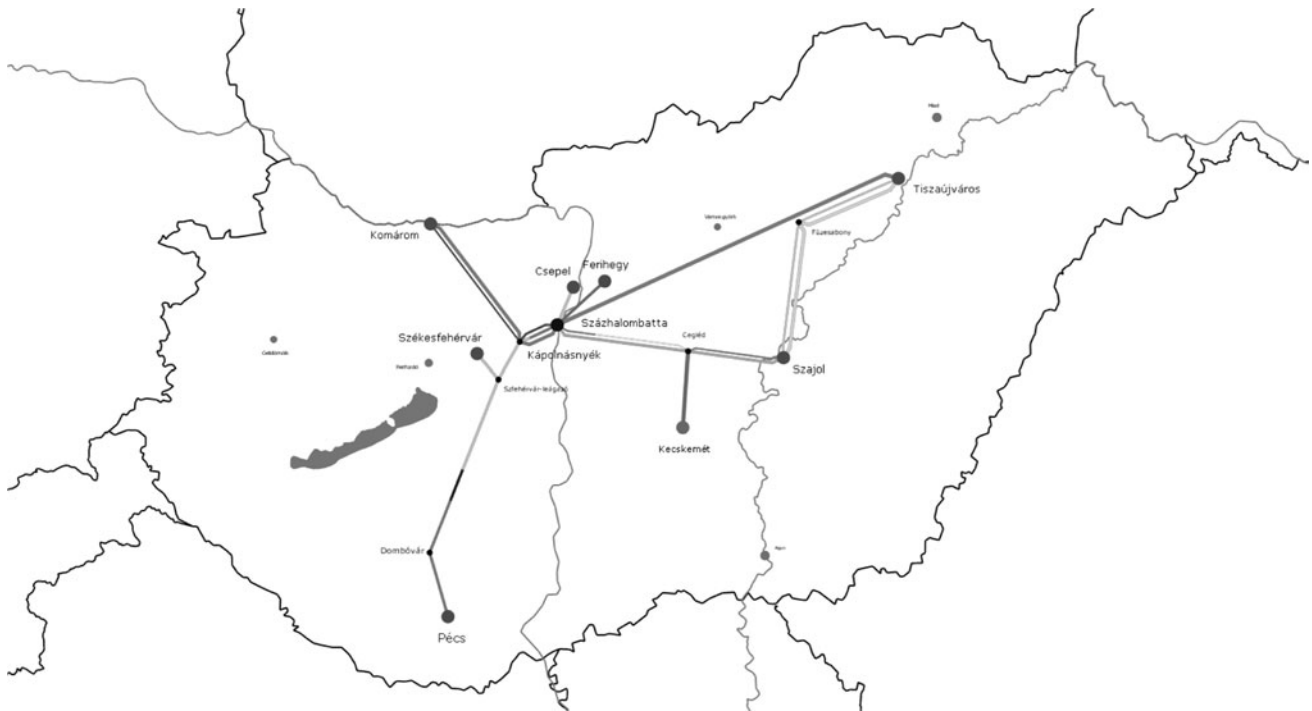


Fig. 1 Pipeline structure of Hungarian part of MOL where lines denote pipes and dots denote refineries and depots

World-wide crude transportation is the central logistics operation that links the upstream and downstream functions and plays a crucial role in the global SCM in the oil industry. Cheng and Duran (2004) have developed a decision support system to investigate and improve the combined inventory and transportation system in a representative world-wide crude supply problem. This system is based on the integration of discrete event simulation and stochastic optimal control of the inventory/transportation system. Its aim is to assist decision makers with the study, design, and control of the world-wide crude supply chain. Uncertainties arising from travel time and crude demand are formulated as a Markov decision process. The solution method for the optimization problem is based on dynamic programming.

Lewandowski (1994) presented an object oriented methodology for modeling a natural gas transmission network. Each element of the network, such as a gas pipeline segment or a node, is represented as an object, which is assembled into a network. This methodology has been implemented using a collection of C++ classes for structured modeling of dynamic systems. This collection of classes makes it possible to simulate hierarchical dynamic systems using the state variables and sub-models as components of a model.

Herrán-González et al. (2009) focused on the modeling and simulation of a gas distribution pipeline network with a special emphasis on gas ducts. Gas ducts are the most important components of such systems since they define

the major dynamic characteristics. Two simplified models have been presented which include the inclination term, neglected in most related articles. MATLAB and Simulink have been applied to solve three examples. The results are compared with the existing ones in the related literature.

Lasschuit and Thijssen (2004) have presented a decision support tool for supply chain planning and scheduling in the oil and chemical industry. The system provides a coherent framework, including mechanisms which allow consistent economic and operational steering, taking real-time information into account on actual operations and market economics. The resulting mathematical programming model is a mixed-integer non-linear programming (MINLP) model: integer aspects arise because of fixed costs, investment costs, cargo costs, and tiered pricing. Non-linear relations are mainly caused by economic variables and non-linear unit operations.

Neiro and Pinto (2004) have introduced a general framework for modeling petroleum supply chains. Different models have been proposed for tanks, pipelines, and refineries. The connected models have a complex topology based on which an MINLP problem is formulated. Rejowski and Pinto (2008) generalized the above methodology from discrete to continuous time frame.

MirHassani and Ghorbanalizadeh (2008) presented a modeling framework for a real-life scheduling problem in an oil company. The problem consists of several refinery tanks, one multi-product, multi-branch pipeline, and some distribution depots. Their MIP model is based

on discrete-time and a division of the pipeline by equal size segments.

Kim et al. (2008) and Fan et al. (2009) have proposed a paradigm for optimally designing an enterprise-wide supply network. It resorts to the efficient graph theoretic method based on P-graphs (process graphs). In the broadest sense, a supply network is, in fact, a process network. The method simultaneously yields not only the optimal but also the near-optimal networks in ranked order in terms of the objective function.

Pootakham and Kumar (2010) have presented a study of the life cycle assessment of the transportation of bio-oil from a centralized site (supplied with forest biomass) to an end user. Two types of transportation have been considered and compared: pipeline and truck.

The efficient use of energy is a very important issue for the processing industry. Klemes and Friedler (2010) have presented the advances in process integration. The impacts of energy generation, transport, and consumption systems on environmental pollution have both local and global effects. Over the years there have been various powerful methodologies developed to cope with those problems. Klemes et al. (2007) have proposed a novel evaluation tool for energy saving.

System architecture

The proposed decision support and simulation tool is named ProdSim which refers to product pipeline and tank simulation. Figure 2 illustrates the inputs and outputs of ProdSim. The current state of the logistics system is known, which is the content of product tanks and the product pipelines. Tanks at a given site may be handled individually or in an aggregated way. The former means

that the operator specifies exactly which tank is the target of a transport, while in the latter, only the target site is given. The state information is updated regularly. If all the operations are carried out according to the schedule, then the update only confirms the simulated values.

The physical layout and the properties of the simulated system are also known. Providing information about the products, tanks, sites, and pipeline structure is the modeling step, mapping a real-life system into a conceptual model. The application is flexible as the underlying model can be easily changed. The product pipeline network is highly complex, e.g., there are branching points at various locations, parallel product pipelines, the pipe diameter may change between two sites, and the direction of the flow can also be reversed.

Each tank is dedicated to a single product (since different products require different infrastructures, e.g., mixer, tap), but this assignment can be changed if certain conditions are met. The capacity of each tank has two components: mobile and immobile part. The immobile part cannot be downloaded in regular operation.

Demands for different products are known in advance; these include the type of the product, its amount, and delivery time. Only refinery sites have blending capability, other sites just store and distribute products. Products are transported by barges, railway tank cars, trucks, or product pipelines. Demands may change over time, which has to be taken into consideration.

An operator specifies the future operations by defining the blending order schedule, the product pipeline schedule, and the allocation of products among modes of transportation. Product allocation determines the blending order, the transportation order through pipeline network, and other material movements (export, domestic sales, and import). Product pipeline schedule can be described by the

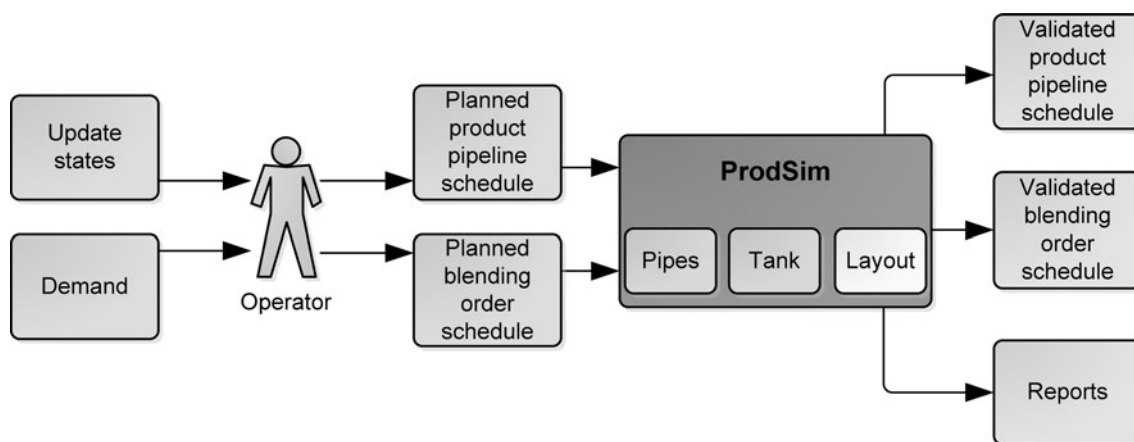


Fig. 2 The inputs and outputs of ProdSim

three main operations: upload, download, and transport. Upload typically occurs on a supply site after a refinery produced the desired product; download usually occurs on both demand and supply sites where the product is handed over to the customer. For us, the term transportation means only the transport in a product pipeline and not any other means of transportation such as barge or railway. Different types of liquids are transported through a given pipe after each other. MOL has deemed that the effect of mixing neighboring liquids can be neglected from the scheduling point of view. Two liquids sent from the same location may have different destination sites. Beginning and ending points of the liquids within each product pipeline are calculated. The system can indicate when a liquid reaches a branching point when the valves have to be set into a new position. Motion of the liquid in a product pipeline is driven by the currently pumped liquid at the source. It may happen that transportation of a liquid is needed just to drive a liquid already in the pipe.

The output of ProdSim is the feasible and achievable product pipeline schedule, blending order schedule, product allocation, and future states of the system as it evolves in the simulated time period. The operator plans the schedules and checks its feasibility with ProdSim. The future states of the system can be given with high precision either in the form of printed reports or in a visualization module, where the changing content of tanks and product pipelines can be displayed.

Figure 3 displays the functional parts of ProdSim: the administration module, the simulation engine, the visualization module, and the underlying database. The first three modules are used directly in the simulation process; the fourth one is used indirectly. The administration module is a client program which is connected to the database server. The client can be installed onto any PC. The simulation engine operates on a dedicated server. It may require some

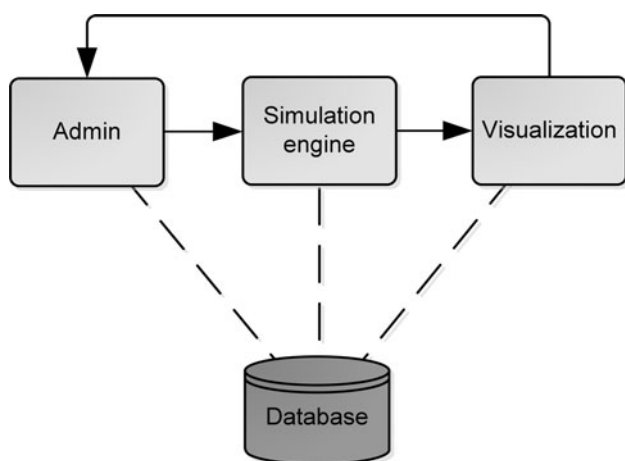


Fig. 3 The functional structure of ProdSim

time as it involves a great number of SQL queries and heavy computation. Results are also shown in the client program. The changing content of each product pipeline can be displayed, as well as the levels of tanks can be compared, or potential inconsistencies can be highlighted. Berning et al. (2004) proposed a similar module for monitoring production schedules graphically.

Performing a simulation has three main steps: (i) providing the input to ProdSim: the planned product pipeline movements, blending, planned sales, and the updates of the current system state, (ii) running the simulation, (iii) visualization, and analysis of the results to assist the decisions in supply and distribution. In case of an inconsistency, the whole process has to be repeated.

Simulation engine

The implemented system realizes the simulation of the previously mentioned processes. Process simulation is chosen instead of optimization since an objective function is very difficult to articulate; there is no exact method for a department to determine the cost coefficient corresponding to the decision variables. In SCM there are complex constraints which are hard to formalize in a mathematical model (e.g., expected stock levels, demands in case of price changes, supply push, and demand driven periods in blending). In this simulation framework, the overall decision is in the hand of the operator; however, this simulator is an effective tool to support the planning process.

Simulation determines the behavior of a given system based on planned operations (e.g., pipeline transportation, tank upload and download, etc.) in given time intervals. It is implemented by calculating the new states of the system minute by minute. In each minute, exactly one calculation is performed for each component (e.g., material level of pipes and tanks, etc.) of the system so that their new states can be determined. The system states are only saved once per hour in order to accelerate the data processing during the visualization. This does not compromise accuracy from the visualization point of view because when a graph is created, for example, from the changing content of a tank, the time horizon is measured in days. Moreover, the exact level of a tank is stored for important times, e.g., the starting time of a download. Consequently, the result of the simulation is stored hourly into a database which gives an adequate basis for graphical visualization of the calculated data. As none of the simulation systems, ProdSim is neither capable of mapping the reality to a 100%, but it can flexibly handle the difference between the logical and the real system. These differences can arise from inaccurate calculations, model incorrectness, unplanned activities, etc. If any of the previously mentioned incorrectness occurs,

ProdSim enables manual correction of the data in order to eliminate errors.

Components of the simulation

Every piece of information which describes the physical system (e.g., structure of the pipeline network, parameters of sites and tanks, etc.) is retrieved from the database. Thanks to this; there is no need for altering the simulation framework itself if the underlying physical system has been modified or extended; only the model has to be revised. For instance, if a new tank is installed at a site, then the system model can be modified accordingly.

In the course of simulation the following four objects of the real system are involved: pipes, pipe branching points (pipe connections), tanks, and sites. Their input data are retrieved from the database such as the activities during the simulation.

A tank object contains several important parameters. It has an immobile level which usually cannot be downloaded with the usual method, and a mobile level which gives the usable storage capacity. The sum of these two values is the maximum capacity of a tank. Tanks can be handled individually or in an aggregated way depending on the tank managed parameters of the given site. One product is assigned to each tank; occasionally it can be changed. A tank can be uploaded and downloaded simultaneously through its taps. Every tap is associated with a pump which determines upload and download speeds. The tank object contains some other parameters like the owner of the given tank and the site where it can be found, etc. Tank level can be changed by upload and download. For instance, in Fig. 4 two parallel downloads (1st download: 6–13 h, 2nd download: 11–20 h) are depicted. These two downloads are merged during 11–13 h time interval.

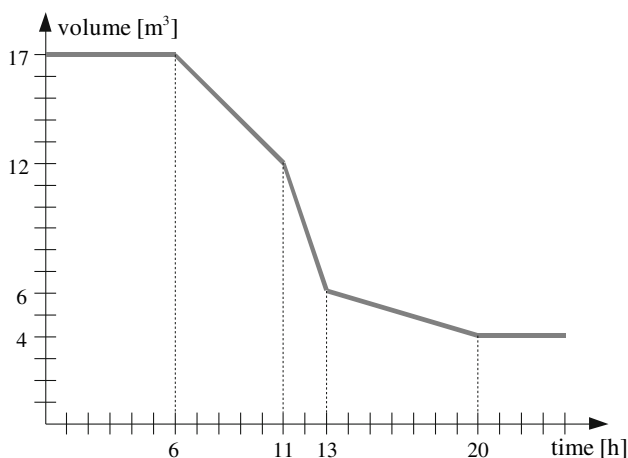


Fig. 4 Tank download

The important parameters of a pipe object are the following: starting and ending point, diameter, length, and volume. Pipe connection objects contain three important data. The first is the site identification which determines the site where the given connection is located. The other two are pipe identifications of those pipes which form the connection in question. From the simulation point of view, the most important parameter of a site is a logical value which determines whether the tanks are handled individually or in an aggregated way. During the simulation, materials are transferred through the pipeline network from a tank at a given site to another tank at another site. Figure 4 shows an elementary step of product transport in a pipeline. In the first step, the pipe contains 95-MON gasoline with 5% bio ethanol (called Mogas 95/E5 in short) and 98-MON gasoline (Mogas 98) which is uploaded currently. In one elementary time step some Mogas 98 is uploaded into the pipe; simultaneously the same amount of Mogas 95/E5 leaves the pipe, see Fig. 5.

The list of activities defined by the operator is one of the elementary input information of the simulation. The simulation system consists of the following activity types:

- (i) Transportation of products by pipeline network
- (ii) Upload of products to tanks
- (iii) Download of products from tanks
- (iv) Upload of products to sites
- (v) Download of products from sites

The complexity of the simulated system arises from the wide range of connections and dependencies of the different objects. On a tank-managed site, tanks are handled individually; thus, in any action (transportation, upload, download) each tank can be identified unambiguously; as a result, all their parameters (volume and capacity, etc.) are known. Since tanks are controlled by products in an aggregated way on a site-managed site, decision support is needed to allocate the actions between tanks. This decision support is provided by the simulation engine. In the pipeline network, pipe items are connected with different diameters. Owing to this, each pipe item has various transport speeds for the same product. Branching points and bidirectional transportation also contribute to the complexity of the model.

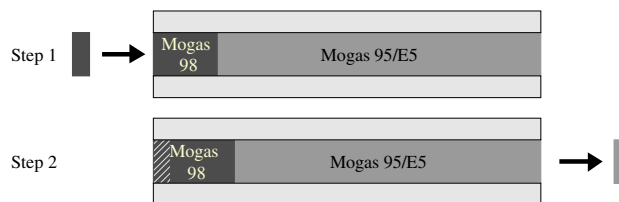


Fig. 5 Two elementary steps of a pipe transport

There is only 5% discrepancy between real and model results for monthly time period when testing the simulation model with real data. Most of the time the simulation period is 4 or 5 days; thus, the discrepancy is much smaller.

The simulation process

The simulation process can be divided into two phases: preparatory phase and the main phase of simulation. At the preparatory phase the states of the system components are loaded from a history. A history is a snapshot of the state of the system at a given time. History is the result of a previous simulation which can be modified manually if discrepancy has been identified. The operator can select from a number of histories which are stored in the database.

In the main phase of the simulation (see Fig. 6) the whole time interval intended to be simulated is covered by elementary (1 min) time steps. In each step, the actual state of each system object is determined and stored in the database at given time intervals (default is 1 h).

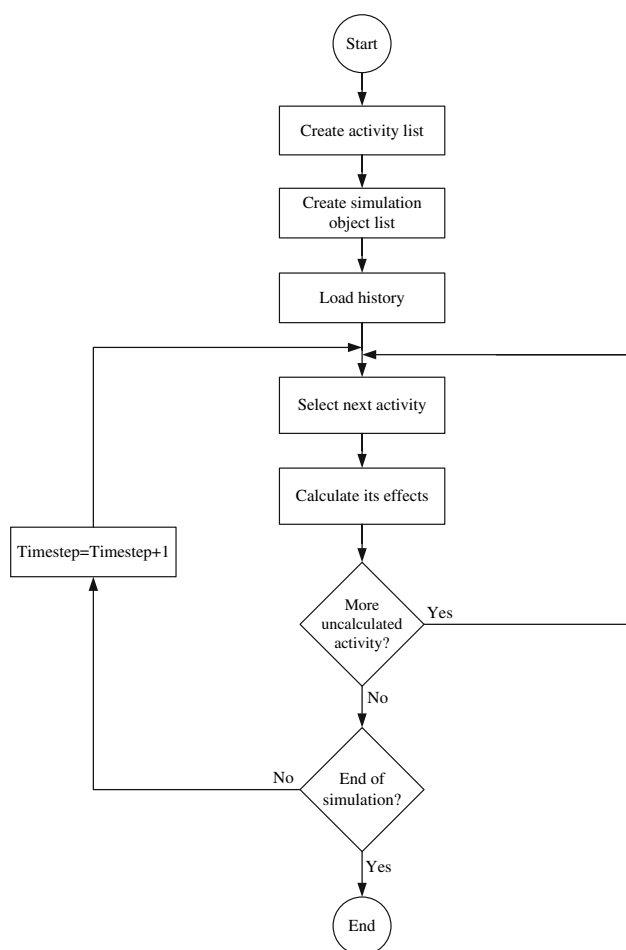


Fig. 6 Algorithm of the main phase of the simulation

In the first step, the algorithm organizes the planned activities into a list according to the order of their planned starting time. Consequently, the list of the objects (pipes, pipe connections, tanks, and sites) connected to the activities is generated. For instance, for an upload the corresponding tank is added to the object list. In the next step, the starting state of the objects and activities is set according to the data of history. After setting the starting parameters the algorithm is continued with the calculation part which is carried out in two embedded loops. The inner loop calculates the effects of each activity which is active at the given time. The outer loop increases time until the end of the simulation has been reached. When the calculation part is finished, the results are saved into the database.

Summary and future work

A simulator and decision support tool, termed ProdSim, has been presented. It is an efficient tool to ensure the balance among product availability, sales, and transport in each production and distribution point; to display the actual schedule and its effects; and to identify inconsistencies such as supply–demand imbalances in the schedule. Results can be presented in legacy reports and charts or in a visualization module which can display the changing content of pipes and tanks.

In the future, ProdSim is to be further improved. Specifically, a much tighter integration is envisioned between ProdSim and the other systems of MOL; more elaborated and interactive visualization and scheduling form will be designed. This would greatly reduce the burden of the operators and ease the use of ProdSim.

It is also our intention to ease the design of the product pipeline plan and the blending order schedule. This can be done by formulating and optimizing a mathematical programming model. In this scenario the task of the operator is to carefully set the parameters of the model and to supervise the system.

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