DISCRETE EVENT SIMULATION IN THE DESIGN, LAYOUT AND SCHEDULING OF PIPELESS BATCH PLANTS

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A way forward in multi-product manufacturing is the emerging technology of "pipeless plants". The basic idea of a pipeless plant is to move the process vessel between fixed stations for mixing, separation and other activities. The elimination of pipework for the transfer of material offers great flexibility for change, and allows a company to respond quickly to market demands and technological advances. As well as reduced downtime for product changeovers, and the ability to introduce new products without too much modification, other benefits include reduced product loss, ease of cleaning, and reduced inventories (Just-In-Time processing). Little research has been found on the safe design of pipeless plants, which can be split into three aspects: process, computer-control, and schedule. This paper is focused on the subject of scheduling. Although little published literature is available, papers on the subject have worked on the premise that a correctly working schedule would overcome the safety issues. However, scheduling is usually concerned with optimum product output, and is not adequate from a safety perspective, as demonstrated in this paper. Layout and scheduling have to be considered simultaneously in the design of a pipeless plant, and a method of analysing the interaction between the two is required. This paper illustrates the value of discrete event simulation (DES) both as a design tool and as a hazard identification tool, by taking a published schedule and simulating it using ARENA Simulation Software. Several issues are raised such as where vessels start from and where they finish, and the rules that they must follow on each leg of their journey. As well as revealing potential problems, discrete event simulation enables the designer to propose alternatives, and explore them. The result of which should be an optimum schedule, both in terms of output and safety, for a proposed layout.

Keywords: discrete event simulation, design, safety, pipeless plants

INTRODUCTION

In technical terms a pipeless batch plant is an arrangement of many units, such as movable reactors and other functional stations, which work co-operatively by avoiding collision or conflict[1]. To understand this it can be likened to a chemical laboratory[2], where a beaker or flask could be a "mobile vessel", and the laboratory equipment such as the Bunsen burners are "processing stations". Usually all the operations required to produce a product are carried out in a single flask which is moved around to different processing stations. Therefore the basic idea of a pipeless plant is to move the process vessel between fixed stations for mixing, separation and other activities. The elimination of pipework for the transfer of material enables pipeless plants to be more flexible than conventional batch plants. Other benefits include reduced product loss, ease of cleaning, and reduced inventories (Just-In-Time processing) [3]. Companies, mainly in Japan, already consider pipeless plants to be beneficial to their business requirements[4-6]. However, the flexibility that the pipeless plant offers, which allows changes to be made quickly and easily introduces new hazards. Changes always need to be considered carefully before being implemented.

There are a small number of papers written on the subject of pipeless plants. The majority however have not considered the safety issues in any depth. These are in terms of the sharing of resources, problems with certain process operations (leading to thermal runaways), human involvement (batch processes involve numerous startups and shutdowns), movement of vessels (crossing paths on a network of tracks), and altering of set-points for control (such as level and temperature) for each batch. These issues can be examined under three main aspects of safety in the design of computer-controlled pipeless plants: process, computer-control, and schedule. Some of the issues concerned with process safety have been described elsewhere[7], and would pick up problems with cross-contamination, double-charging etc. in the same way as in a conventional multi-product batch plant. Computer-control safety is being looked at, but the focus of this paper is schedule safety which deals with the movement of vessels. Papers written in this subject consider that a correctly working schedule would overcome many of the potential safety problems. This assumption is sound as long as no other problems occur in the plant such as sensor failures, which allow the plant to continue running or a vessel to continue moving, even though a hazardous situation has developed. These kinds of problems should be picked up in the Hazop or when investigating the safety of the computer-control system. The issue now is how to verify that the schedule is correct, for the given plant layout. Obviously it would be advantageous if this could be done before the schedule is implemented on the real plant.

Realff et al argue that the design, plant layout and scheduling need to be considered simultaneously[8]. They present a mathematical formulation for their combined problems, using the short-term scheduling formulation of Pantelides et al[9]. The formulation applies the constraints governing the design, layout and operation in terms of parameters and variables describing the existence, layout and utilisation of processing stations, and the number and utilisation of the transferable vessels. A decomposition procedure for the solution of the large mixed integer optimisation problem resulting from the formulation was proposed. The procedure employs an aggregate description of the plant operation to determine appropriate equipment selections and layouts at an outer level, while the inner level determines the number of transferable vessels and a detailed operating schedule. It is interesting to note that when the proposed procedure was applied to their example problem, the first three designs offered by the outer level were suboptimal.

Scheduling is usually concerned with optimum product output, and is not adequate from a safety perspective. One of the most prominent dangers associated with moving vessels is the possibility of collision. To overcome this, or minimise the possibility of this problem, the plant layout and schedule require careful consideration together. The course a vessel takes together with the time that it travels on each leg of its journey needs to be analysed. Intersecting routes should be avoided as much as possible so as to reduce the chances of vessels crossing each other's paths, especially in case of failure. However, it is not feasible to completely avoid intersections and accordingly the layout and schedule should be created to minimise the risk of collision. Therefore scheduling cannot be considered independently of routing, and a method of analysing the interaction between the two is required. One way to do this is through discrete event simulation (DES).

Discrete event simulation can be used as a hazard identification tool and can help to:

1. Show the importance of explicit behaviour specification, i.e. the simulation software will not allow you to proceed until every single item that is involved has been specified explicitly. These items can be missed in real life, but the simulation software flags them as errors, so that no assumption or missing information is taken for granted.
2. Show the location of possible collisions between vessels.
3. Show the effects of failures to particular items, such as a station or a vessel, on the overall plant.

Simulation can also be used as a design tool. It enables the designer to propose alternatives, and explore them. This is much faster, cheaper and easier than building a plant and then finding problems that would be very expensive to put right.

PROCESS DESCRIPTION

To illustrate the usefulness of DES, a simulation of the process described in the paper by Realff et al[7] was created. The process has the following steps:

1. A clean vessel goes to a Charging Station, where it is charged with Feed A. Both Charging Stations have the same feed.
2. The charged vessel then goes to a Reaction Station where a product, ProdA, is formed. Both Reaction Stations can carry out the task, but Reaction Station A is faster (and more expensive).
3. The vessel can then be discharged to an external storage tank (ProdA), thereby leaving an empty (essentially clean) vessel, or go to a Mixing Station. Both the Mixing Stations are the same.
4. At the Mixing Station the vessel contents can be blended with additives A1 or A2. The corresponding products Prod1 and Prod2 are discharged to external storage tanks directly from the Mixing Station.
5. The empty, soiled vessels must then be cleaned before re-use.

PLANT LAYOUT

The plant layout considered has a “herringbone” structure, which can accommodate up to eight processing stations, up to four stations can be on either side of the centre track, which is bi-directional. No more than one vessel at a time can occupy a station. Realff et al[8] conclude that the optimum plant to produce the maximum amounts of all three products on a daily basis, comprises 7 processing stations and 6 transferable vessels.

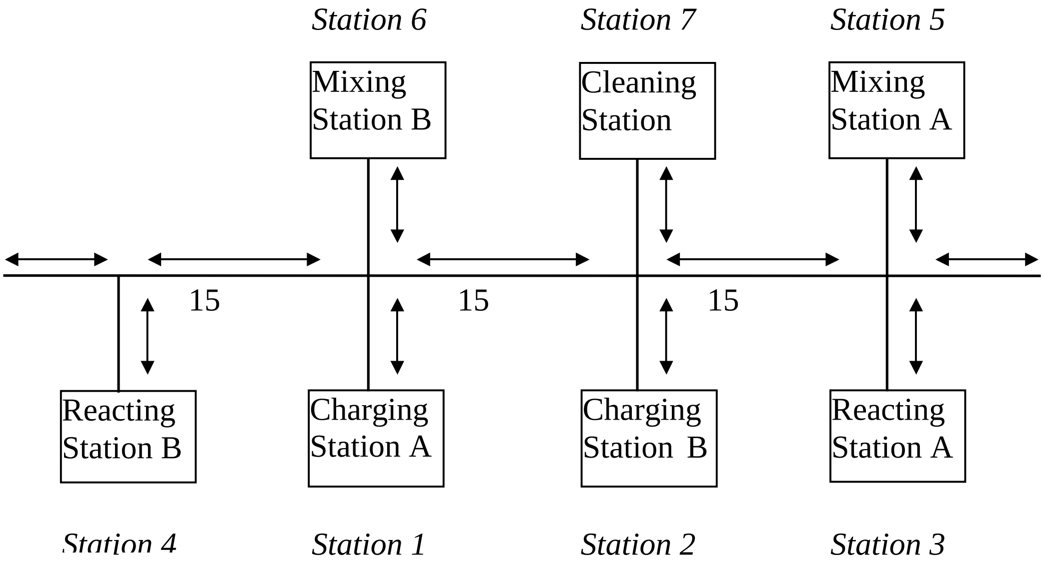
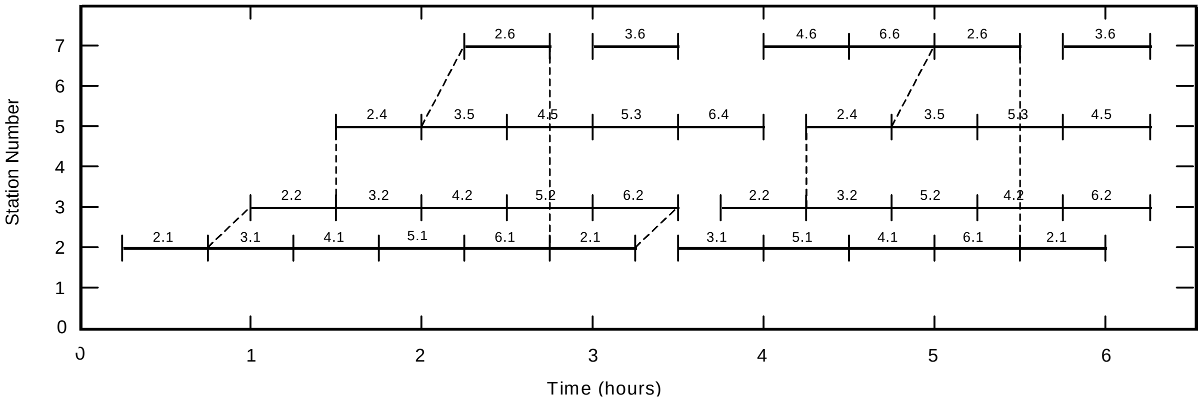


Figure 1: Plant Layout

It is assumed that travelling time between stations opposite each other is zero, and between stations adjacent to each other is 15 minutes.

THE SCHEDULE

The suggested schedule for the first 12 hours of the case study is shown in Figure 2.



Key to Tasks:

x.y

x: vessel
y: task

1: Charge
2: Reaction
3: Discharge A
4: Mixing 1
5: Mixing 2
6: Cleaning

Figure 2: The Schedule

The initial progress of Vessel 2 can be followed on the schedule:

0:15-0:45	Charging at Charging Station B (Station 2 on schedule)
0:45-1:00	Travelling from Charging Station B to Reacting Station A
1:00-1:30	Reacting at Reacting Station A (Station 3)
1:30-2:00	Mixing with A2 at Mixing Station A (Station 2) Assumes zero travelling time between station as they are opposite
2:00-2:15	Travelling from Mixing Station A to Cleaning Station
2:15-2:45	Cleaning at Cleaning Station (Station 7)
2:45-3:15	Charging at Charging Station B (Station 2) and so on...

For the simulation this series of steps can be translated into a sequence that Vessel 2 follows while travelling around the plant, including the duration it is stopped at each station.

Since the processing time for Reacting Station A is less than Reacting Station B, and it is a shorter distance from Charging Station B, it is primarily used for the reaction step. Both Mixing Stations are the same, however, Mixing Station A (Station Number 5) is used because it is directly opposite Reacting Station A so the travelling time is very small. Three operations are performed at the mixing stations: discharge of ProdA; addition of A1, and then discharge of Prod1; addition of A2, and then discharge of Prod2.

After the discharge of any product, a vessel is cleaned before being used for the next batch. The suggested plant layout has the Cleaning Station located opposite Charging Station B in order to reduce the time that the vessels are empty, clean and not in use.

Vessel 1 does not enter production until 10:45 hours. It is assumed to have travelled to Charging Station A (Station Number 1), and remained there until required. This would explain why Charging Station B (Station Number 2) is primarily used for the first 12 hours.

SETTING UP THE SIMULATION

The plant described above was simulated using ARENA simulation software[10]; to investigate the performance of the schedule proposed by Realff et al[8] for the layout. The simulation was specified as close as possible to the case study as described. When setting up the simulation it was discovered that certain points were not described in the case study such as where the vessels started from or whether they could pass each other on the track or at intersections. Other details such as vessel sizes or vessel speeds were also not specified and had to be assumed. At the start of the simulation the software checks the specifications required and will not allow the simulation to run flagging any unspecified items as errors. This meant that vessel sizes, vessel speeds, network paths, track lengths and directions, processing times in stations etc., see Table 2, could not be overlooked as they would be flagged. In trying to set up the simulation the importance of explicit behaviour specification became evident, and the exercise showed not only the importance of DES as a hazard identification tool, but also its usefulness as a design and specification tool. It would also aid in the communication of ideas between the designers.

Parameters	**Value**
Vessel size	1 unit
Vessel speed	1 unit/minute
Track length between adjacent stations	15 units
Track length between opposite stations	2 units
Charging time	28 minutes
Reaction Time	28 minutes
Mixing Time	28 minutes
Discharging Time of A	28 minutes
Cleaning time	28 minutes

Table 1: Values of Parameters as used in the Simulation

The travelling time between stations opposite each is specified in the paper as 0 minutes. However, in the simulation the vehicles have a definite size (of 1 unit), therefore the track length leading to the station cannot be 0 units (it has to be 1 or more) otherwise the vehicle cannot enter. This means that it takes the vehicle 1 minute to enter and 1 minute to leave each station. The processing time for every operation is specified in the paper as 30 minutes. Therefore by using 28 minutes for processing times in the simulation, with 1 minute to enter and 1 minute to leave each station, the time spent at each station is 30 minutes.

RUNNING THE SIMULATION

Once the plant and schedule had been specified Arena attempted to run the simulation. However, the simulation could not keep to the specified schedule, and eventually terminated, flagging up errors such as vessels moving in opposite directions on the same tracks. This happened as a result of delays forced upon vessels in the plant, due to having to wait at intersections or at stations. Consequently subsequent batches were introduced before the preceding ones had completely finished. As a result more vessels than specified in the schedule were moving around in the plant leading to traffic congestion. A number of problems were identified and these had to be solved before the simulation could run to completion.

POINTS FOR DISCUSSION

- Starting Points for the Vessels
- Intersections
- Vessels returning to the start after the completion of a batch
- Vessel breakdowns
- Number of vessels used
- Issues of cross-contamination and double-charging

STARTING POINTS FOR THE VESSELS

There was an immediate problem with the schedule, as it is not specified where each of the vessels starts. The first batch starts after 15 minutes at Charging Station B; therefore it appears from the schedule that the first vessel enters the plant at the right hand side. After charging is complete (30 minutes) the vessel goes to Reaction Station A, and after 30 minutes processing time it goes to Mixing Station A for another 30 minutes before going to the Cleaning Station (for 30 minutes). The subsequent batches carry out the same sequence. It is not possible for the vessels to enter the plant from the right, follow the sequence and keep to the schedule published. The vessels are all using the same section of the main track, travelling in both directions. It is not specified as to whether or not the vessels can pass each other on the track, however, common sense would imply that the vessels cannot pass each other on the same length of track, otherwise plant layout and scheduling would not be an issue. One other possibility is for each track to have two lanes, but this is not stated in the paper. Therefore assuming a one-lane track where vessels cannot pass each other, the only way to enable the vessels to follow the sequences of actions in the production, is to introduce delays and therefore the schedule as published does not work.

Starting the vessels at the left-hand side of the plant would reduce some of the delays by reducing the traffic in that particularly busy section of track. To make the simulation as close as possible to the published schedule the first vessel started from the right hand side of the main track, and all the rest started from the left. One possible way of reducing delays in production is for a number of vessels to be able to be waiting at the intersection at Charging Station B, thereby reducing the time that the station is unoccupied (and idle). However, parking areas have not been specified in the paper, so the vessels would have to wait on the track before the station. As there is no production going on in the left side of the plant, and as long as the vessels arrived at the intersection to Charging Station B at the correct time then there is no need for them to wait on the main track, which would just lead to more congestion.

The starting points of each vessel must be specified and taken account of in the schedule. Ideally for simplicity and safety they should start from the same specified parking place, which should be as close as possible to one of the Charging Stations.

INTERSECTIONS

The issue of vessels passing each other, at intersections, causes a real problem at the intersection between Mixing Station A and Reacting Station A. At time 1:45 hours, Vessel 4 has to go from Charging Station B to Reacting Station A, arriving at 2:00 hours. However it cannot enter the station as it is already occupied by Vessel 3. Therefore Vessel 4 has to wait at the intersection. The next station in the sequence for Vessel 3 is Mixing Station A, which it cannot go to as it is already occupied by Vessel 2. The next station in Vessel 2's sequence is the Cleaning Station. To do this it must pass Vessel 4, waiting at the intersection. This would only be possible if Vessel 4 had actually gone through the intersection and waited at the other side. This particular scenario occurs several times at the same intersection during the first 12 hours of the schedule, i.e. at times 2:30, 3:00, 4:45, 5:15, 5:45, 6:45 etc. Basically every time that Mixing Station A and Reacting Station A are occupied and the next vessel has been charged and sent to Reacting Station A. The rules of movement through intersections have not been specified in the original paper. At other points in the plant, such as at the charging stations, the vessel must wait before the intersection so there is no problem for the vessel being charged exiting the station, and moving in a particular direction. It would be difficult to program vessels to treat each intersection differently. The easiest and safest way to run the plant would be to specify the intersection rather than the vessel. Rules are required to specify where the vessels wait for all intersections. Therefore it does not matter which vessel it is, or what stage in the production schedule has been reached, the positioning of the vessel is always known.

VESSELS RETURNING TO THE START AFTER THE COMPLETION OF A BATCH

There is a problem with vessels returning to the start after they have completed their tasks and been cleaned, because of the next vessel coming into the plant. In the paper because the Cleaning Station is opposite Charging Station B, most of the time the schedule shows that as soon as the vessel has been cleaned it immediately starts the next batch, and does not leave the plant. However, at certain points all four stations (Charging Station B, Reacting Station A, Mixing Station A and Cleaning Station) are occupied. The only way for the vessels to proceed with their sequences is for the Cleaning Station to be made available, but the vessel cannot enter Charging Station B as it is occupied, so the options are either to wait on the track (increasing congestion) or for the vessel to leave the plant. In addition, at time 3:30 hours, Vessel 5 completes its run, and then is not shown on the schedule until it starts its next batch at 4:00 hours. It cannot wait on the track, as it would interfere with other vessels, therefore to maintain the schedule it must exit the plant to the right, and then re-enter from the right at the start of the next batch. When it re-enters it will encounter the same problems as described in the previous section on starting points. Due to delays being introduced to overcome the other problems in the simulation, it could not be guaranteed that immediately after cleaning the vessel could go to the charging station. In reality any delay at all from vessel breakdowns to erratic processing times would lead to the problem of a vessel that, after having being cleaned, could not immediately start the next batch. However, the vessel cannot remain in the station, as it is needed for the next vessel, and can only wait on the track as long as it doesn't interfere with movement of other vessels. Therefore the safest option again is for the vessel to leave the plant, and then re-enter when it is required for a subsequent batch. Leaving and re-entering to the right of the plant is the quickest way, but it also creates more problems. Leaving to the left of the plant is much safer, but takes longer as it is a greater distance from the Cleaning Station. Since the vessels enter from the left it is more logical for them to return to their starting point when not in use. The best option would be for the vessels to leave directly from the Cleaning Station.

VESSEL BREAKDOWNS

The paper has not specified any parking stations or any way to remove vessels from the plant in the event of a breakdown. As the paper is concerned with the design, layout and schedule together some thought should be given to what would happen should a breakdown occur. The vessel needs to be removed, and maybe even re-introduced, with minimum interruption, if any, to the schedule.

NUMBER OF VESSELS

Realff et al (1996) specified that the optimum number of vessels is six. However in the schedule for the first 10 hours 45 minutes only five vessels are used, with real problems of congestion. A sixth is introduced which just adds to the problems. By reducing the number of vessels the congestion can be eased and the plant can be run more smoothly, however the productivity will be down. On the other hand, it is a waste to have six vessels and use only five of them for nearly 11 hours out of 12. Therefore another layout is required, that will make better use of the vessels.

ISSUES OF CROSS-CONTAMINATION AND DOUBLE-CHARGING

Cross-contamination and double-charging is a problem as in any multi-product plant. In this particular case both charging stations are the same and therefore going to the wrong station makes no difference. Additives can be added at the mixing stations, which are also the same, with a choice of two additives. The problem of charging the wrong one could normally be picked up in a Hazop on the design of the plant, looking at deviations such as ‘charge other than’ and picking up any hazardous consequences or operational problems. This would indicate and record any particularly undesired scenarios. A vessel inspection after the cleaning station may also be required which is a step in the Hazop of pipeless plants[7]. In a pipeless plant as long as a recipe includes a specific list of stations to visit to make a product then only the necessary raw materials should be charged. A rigid schedule is an advantage here as a particular vessel is expected at a particular station at a specific time, and the vessel not arriving at that time, or a different vessel arriving would issue an alarm for the operator to deal with.

CONSIDERING ALTERNATIVES

The aim of the plant is to manufacture products as quickly and safely as possible. In business productivity will not be totally surrendered for safety. The best plant would be one in which the productivity is high and safety is acceptable, rather than one in which safety is exceptional and productivity is average. In the simulation it is necessary to introduce delays into the published schedule to make it work, but with reduced productivity. To overcome the problem at the intersection between Mixing Station A and Reacting Station A, as described above, the schedule has to incorporate a total delay time of 1 hour 45 minutes in the first 12 hours (since the problem occurs 7 times). There are other possible solutions, such as altering the plant layout, instead of introducing delays. However it is much simpler to alter a schedule than the layout, therefore altering the layout should be considered only if the new layout significantly improves productivity.

One way to alter the layout is in terms of the positioning of the stations, such as the Cleaning Station. Although this does save travelling time in some instances since some of the stations are now closer together, it also adds time in others, and overall cannot be significantly improved from the layout as described in the paper. In addition to this it is not desirable to change the layout continually.

Another possible modification would be to include a loop into the layout whereby the vessels can return to the start after they have completed their tasks. This tackles some of the issues described previously in terms of:

- The starting points of the vessels
- The problems encountered at intersections

- Vessels returning to the start after completion of batches
- Vessels can be removed more easily in the event of problems such as breakdowns.

The problem of collisions between vessels travelling in opposite directions on the same track is greatly reduced, especially if the loop is uni-directional. In addition some of the delays introduced before the initiation of batches can be removed. Removing the delays will improve the productivity, however, the time taken to travel around the loop could be significant. This time would not matter as long as there were enough vessels to continue production (may require more than six). In the published schedule only five vessels are in use at any time.

Figure 3 shows the loop running from either end of the central track. This is the simplest positioning of the loop. The vessels may enter from the left side and leave the plant at the right side, following the loop back to the start. This reduces the traffic congestion on the main track. Vessels may also be removed from the loop for maintenance. The main drawback as described previously is the distance the vessel has to travel around the loop and therefore the increased travelling time (a minimum of one hour for the vessel to travel from the Cleaning Station back to the start).

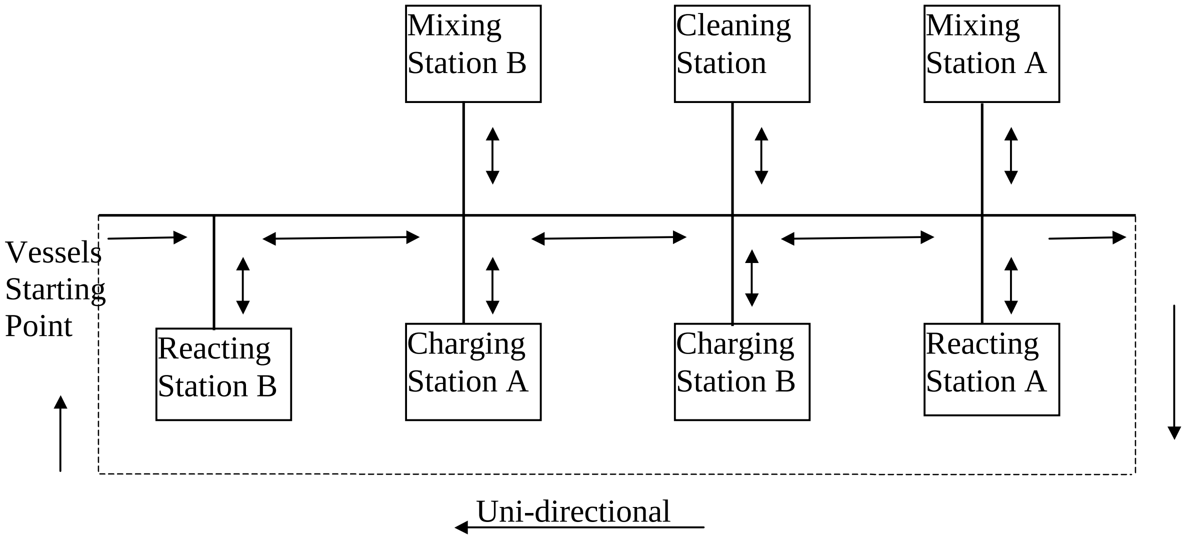


Figure 3: Alternative Plant Layout - External Loop

A simulation of this layout was created. The vessel was given the destination and automatically chose the route that was the shortest distance and therefore never used the loop. The modifications to the original simulation to make it work with the introduction of the delays produced a better production schedule than by using the loop.

Another option could be to have a central loop, i.e. two tracks running parallel with each other, as in Figure 4. This option could however introduce additional safety problems as it proposes even more intersections (eight instead of four). Therefore although possibly solving some of the problems it supplements others.

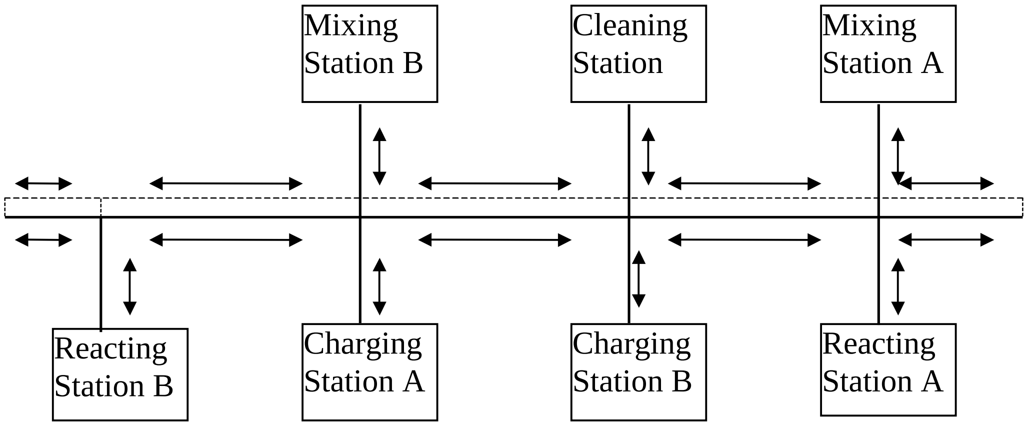


Figure 4: Alternative Plant Layout - Central Loop

As stated before, the best solution would involve the vessel leaving the plant directly from the Cleaning Station to the starting point, as in Figure 5. It solves the problem of congestion, vessels returning to the start after the completion of a batch, vessel breakdowns, and increases productivity.

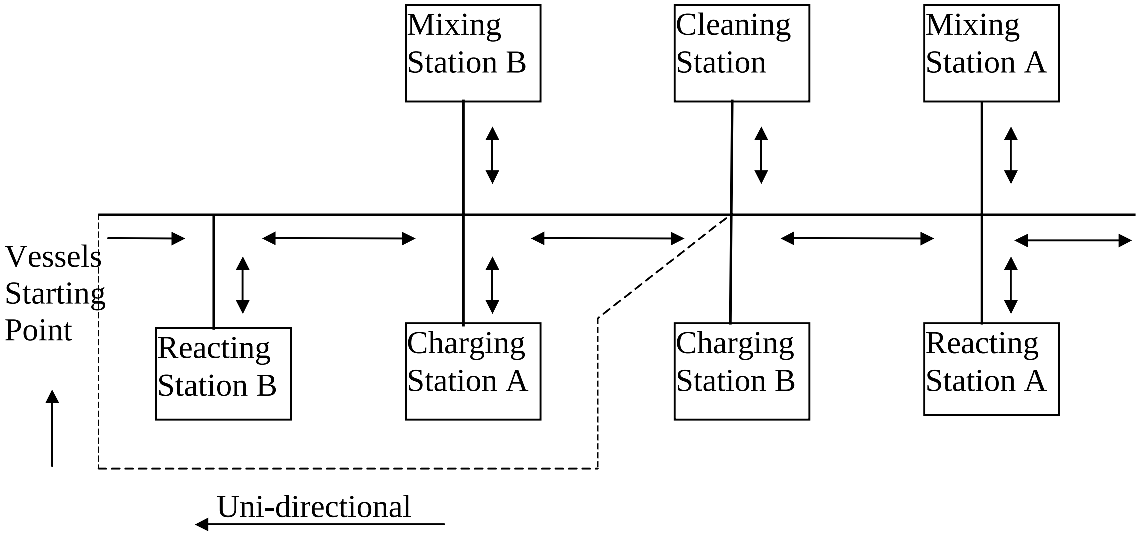


Figure 5: Alternative Plant Layout – Loop from Cleaning Station

Papers, describing a different plant layout, by Gonzalez et al[11, 12] offer an alternative approach by introducing buffers (of infinite capacity) before and after waiting stations and at nodes joining the individual tracks comprising the layout structure (the vessels being allowed to cross paths at the nodes). Although this solves some of the problems outlined earlier such as vessels waiting on the track, and intersections, it introduces others such as priority systems in the buffers and possible long waiting times for products with short shelf-lives. The schedule described in the papers gives an overestimation of vessel transfer times to allow the resolution of transfer conflicts, however, there is no way to know how often the conflicts will occur, and therefore at any given time it is difficult to know the position of each vessel in the plant. The starting positions of the vessels is behind the chargers, without any directive or means to return there, as they can wait in the buffers until required for a new batch. This however leaves the vessels in the plant, rather than out of the way which would be a safer option, and makes a visual inspection of a vessel prior to a new batch more difficult. Although having buffers is a good idea, the vessels would be more free to move around. The information a vessel would use is the final product required with a list of processing stations to visit. Not tied by the same time constraints, there is a greater possibility for a vessel to go to stations in the wrong order or go to the wrong stations. Therefore, although the approach of using buffers may have its advantages, carrying out a simulation would still be required to follow what happens in the plant.

SIMULATION RESULTS

Overall it was found that the schedule could not be made to work precisely, as published, on the ARENA simulation software. It required modifications to the times to incorporate necessary delays for the production to proceed. The delays made the plant slower, and it is possible therefore that the design chosen was not the optimum. Analysis using the simulation software of the different layouts clarified that the best choice in terms of productivity is the loop from the Cleaning Station. Other factors that have to be considered before a loop is installed include available space, safety, and cost.

CONCLUSIONS

The simulation of the case study has given definite indications of the type of problem pipeless plant designs would encounter in terms of layouts and schedules. The simulation has indicated a number of issues that require special attention in the design:

1. The answers are required to three very important questions:
   - Where do the vessels start?
   - Where do the vessels finish?
   - How do they get back to the start at the end of a batch?
2. Intersections require careful consideration. The number of approaches should be minimised. Are the vessels to wait at intersections, and if so do they wait on the track or are parking spaces required? There may be a need to prioritise, and therefore queuing systems would also be required.
3. Broken down vessels need to be removed from the plant for safety. Consideration needs to be given to how this is done. Also whether vessels are re-introduced at the point at which they were removed or whether they should be cleaned of any product and introduced back at the start needs to be examined.
4. Are discharging stations required, or is it possible to discharge directly from the reacting stations or mixing stations? A station dedicated to one particular task should be safer than a station where multiple tasks have to be carried out. However, due to the short shelf-life of some products, having an extra station to which a vessel has to travel to is not such a good idea, in terms of both time and the increased possibility of vessel breakdown.
5. Is only one cleaning station enough? A problem at the cleaning station would lead to the predicament of running out of clean vessels.
6. Future Expansion: there may be a need to add (or even remove) stations later on, due to different products being manufactured, or even alter the track layout. Some designs would limit this option and there the original layout chosen needs to be as flexible as possible.

This paper has successfully demonstrated the usefulness of discrete event simulation. It has been shown that no matter how good a scheduling program is there is always the possibility of error (or that something has been overlooked). Only by simulation of the plant, with the proposed schedule and layout can one be confident that the proposed design will work. Simulation gives the designer a much deeper understanding of what is involved with the project, which otherwise would be achieved by actually building the plant and realising your mistakes.

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