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Emerald Article: Using system dynamics in a discrete-event simulation study of a manufacturing plant

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Using system dynamics in a discrete-event simulation study of a manufacturing plant

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Abstract

Purpose – To provide an example of the use of system dynamics within the context of a discrete-event simulation study.

Design/methodology/approach – A discrete-event simulation study of a production-planning facility in a gas cylinder-manufacturing plant is presented. The case study evidence incorporates questionnaire responses from sales managers involved in the order-scheduling process.

Findings – As the project progressed it became clear that, although the discrete-event simulation would meet the objectives of the study in a technical sense, the organizational problem of "delivery performance" would not be solved by the discrete-event simulation study alone. The case shows how the qualitative outcomes of the discrete-event simulation study led to an analysis using the system dynamics technique. The system dynamics technique was able to model the decision-makers in the sales and production process and provide a deeper understanding of the performance of the system.

Research limitations/implications – The case study describes a traditional discrete-event simulation study which incorporated an unplanned investigation using system dynamics. Further, case studies using a planned approach to showing consideration of organizational issues in discrete-event simulation studies are required. Then the role of both qualitative data in a discrete-event simulation study and the use of supplementary tools which incorporate organizational aspects may help generate a methodology for discrete-event simulation that incorporates human aspects and so improve its relevance for decision making.

Practical implications – It is argued that system dynamics can provide a useful addition to the toolkit of the discrete-event simulation practitioner in helping them incorporate a human aspect in their analysis.

Originality/value – Helps decision makers gain a broader perspective on the tools available to them by showing the use of system dynamics to supplement the use of discrete-event simulation.

Keywords Simulation, Organizational performance, Operations and production management

Paper type Case study

Introduction

A case study is presented of a production planning process in a gas cylinder manufacturing plant. Although the study achieved its aims and provided valuable information that could be used to improve performance, it became apparent that a major factor impacting on the performance of the system was due to the working practices of the sales department. This area was outside the scope of the discrete-event simulation (DES) study so it was decided to embark on a new study, using a system dynamics (SD) approach, to analyse this aspect of the company. The use of a combination of DES and SD been suggested to analyse operations systems by Fowler (2003, 1999), but few examples exist in the literature. Rus *et al.* (1999) use a combination of SD for project planning and training and DES for more detailed project tracking and control. Martin and Raffo (2001) use SD to represent a software development project

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environment and a DES to describe the detailed software development process. In addition, work has been published on representing discrete events in SD models (Wolstenholme and Coyle, 1980; Wolstenholme, 1982; Coyle, 1985; Curram *et al.* 2000) and comparing discrete-event and SD models (Crespo-Márquez *et al.* 1993; MacDonald, 1996; Ruiz Usano *et al.* 1996; Sweetser, 1999).

The case study

The case study company manufactures a range of aluminium gas cylinders for a global market. The cylinders are used in applications such as beverage machines and fire extinguishers. Generally the demand for cylinders is non-seasonal, with the only predictable demand pattern being the annual seasonal variation of heavy and light (weight of cylinders) mixes, associated with demand for beverage (fizzy drink) cylinders. The size of the cylinders range from a diameter of 102 to 250 mm and cycle-times at the various workstations vary accordingly i.e. the bigger the cylinder the longer the cycle-time. The current method of scheduling production is undertaken using a set of complex sequencing rules, built on experience and workstation performance figures. The quality of the products as well as strong market performance have increased the demand for the company's products. In order to achieve high volumes, both factories suffer from a number of common manufacturing problems, including high levels of work-in-progress (WIP) inventory, long production lead-times, moving bottlenecks and poor delivery performance. Principally, cylinders can be grouped into 10 different diameter families each supporting six separate markets. The smallest design change to a cylinder can necessitate a renaming of the cylinder type. Consequently, over the years, such changes have seen the number of cylinder designs offered to the customer reach approximately 250. The effect on production and capacity planning has been an extremely complex exercise when attempting to schedule the best mix of products for manufacture.

The manufacturing process

Each cylinder is manufactured from a diameter-specific bar of aluminium, which is cut into a billet, machined and then prepared for extrusion. Once extruded, the cylinder has its neck formed and is then heat-treated to age (strengthen) the material. An order-specific internal thread is then machined into the neck followed by a compulsory pressure test sequence. Cylinders are then painted (if requested) and accessories are then fitted. A final internal inspection is then undertaken by an outside testing authority before despatch. The single piece basic cylinder design is shown in Figure 1.

The main manufacturing stages are now outlined in more detail.

Saw

Specific diameter aluminium logs enter the factory from the metal park. The logs are cut into raw billets of specific lengths through a single saw unit.

Billet preparation

The next stage of the manufacturing process is the machining of the billets. Billets are given manufacturing codes that describe the size and finish (depending upon cylinder type). Billets are transferred to one of three machine centres depending on size. Generally the larger the diameter of the cylinder, the longer the cycle time. The billet

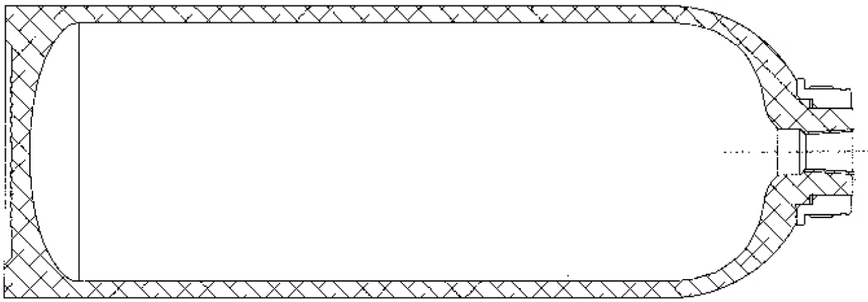


Figure 1.
Basic cylinder design

edges are then trimmed to a specific diameter with the ends being skimmed and (if required) tapered. The billets are then stamped for operator identification and then conveyed (in batches) to the etch process.

Etch

A caustic solution is then applied to the whole billet to allow the adhesion of a lubricant to be applied to the pressed face of the billet. The lubricant is then sprayed onto the pressed face and allowed to dry for 24 hours. The billets are then placed into pallets (in batches), ready for extrusion.

Extrusion

The pallets of billets are loaded onto a shelf where the lubricant is cleaned off the edges. The billets are then loaded onto a conveyor with the lubricated face pointing towards the press punch nose. Once the billet is placed into position, pressure builds up within the punch nose ram and the punch nose then forces the billet against a die. Forced into shape by the punch nose, the punch nose reverses its action and the walls of the cylinder are formed. The now hot cylinder is then transported (by a conveyor) for a compulsory wall thickness test and roll stamping (for identification purposes). If successful, the open-ended cylinder is then transported by a conveyor system to the heading dye, where the basic cylinder neck shape is formed. Once the neck is formed, the cylinders are then inverted into heat-treatment baskets. The quantity of cylinders within the baskets depends upon the diameter of the cylinder. Set-up times for each cylinder type to be extruded at the press will depend upon the length, diameter, wall thickness and base design. Each change of design will require a change of tooling. Generally, the cycle time for extruding each cylinder type increases with the overall increase in the size of the cylinder.

Heat treatment

The baskets are then stacked into oven loading configurations for the heat treatment process which strengthens the cylinders. The capacity of an oven load is inversely related to the size of the cylinder. This has a direct consequence on the overall capacity performance of the heat treatment process. Once the cycle is completed the baskets are unloaded and left to cool (or are quenched in water if required immediately). The basket loads of cylinders are either unloaded manually or through an automatic unloader.

Machining
The cylinders are routed depending upon available capacity and thread finish. A parallel or taper thread is offered into the neck of the cylinder and a collar may also be fitted at the base of the neck for additional strength.

Pressure test
Once the cylinders have been machined, they are then pressure tested. This is a compulsory test for certification processes. Depending upon capacity, the cylinders have two alternative routes for pressure test. All cylinders are then internally washed to ensure no particles are present. Finally, the cylinders are roll stamped and transported on pallets for inspection or painting.

Paint
Any combination of paint finish can be supplied. Once painted the cylinders are then inspected and made ready for despatch. No cylinders can be released from the factory until they have been inspected by an external and independent of inspection body.

The discrete-event simulation study
The use of DES in general as a manufacturing support tool is discussed in Chance *et al.* (1996). Simulation has been used in production planning applications for a number of years. Galbraith and Standridge (1994) present a case study of the transition of an electronics assembly manufacturing system from a traditional push production control system to a just in time (pull control) system. The use of simulation in moving to a just in time system is also considered by Welgama and Mills (1995). Simulation is used by Spedding and Chan (2001) to analyse the propagation of defectives or errors through a manufacturing system. Dewhurst et al. (2001) discuss extending the use of simulation from analysing and designing manufacturing systems to its use as the basis of a methodology for manufacturing planning. A methodology based on Law and Kelton (2000) was used to construct the model which includes model formulation, model translation, verification and validation, experimentation and reporting of results.

Model formulation
Figure 2 shows the process map that provides the framework for the simulation model. The diagram indicates the flow of material through the system and the decision points for logic flow within the system. For instance, all cylinders pass through the saw process stage and then pass through the appropriate billet process dependent on cylinder size. Cylinders with a diameter of 111 mm pass through billet 1, cylinders with a diameter greater than 204 mm pass through billet 2. All other cylinders pass through billet 3. All cylinders then pass through the remaining stages.

The focus of the simulation study itself was on determining a suitable cylinder sequence in order to optimise system performance. Because this is the main experimental factor the simulation model was formulated in order that a cylinder sequence pattern can be loaded into the simulation model from an EXCEL™ spreadsheet.

Model translation
The simulation model was built using the ARENA™ visual interactive modelling (VIM) system (Kelton *et al.* 2002). This is widely used software in manufacturing and

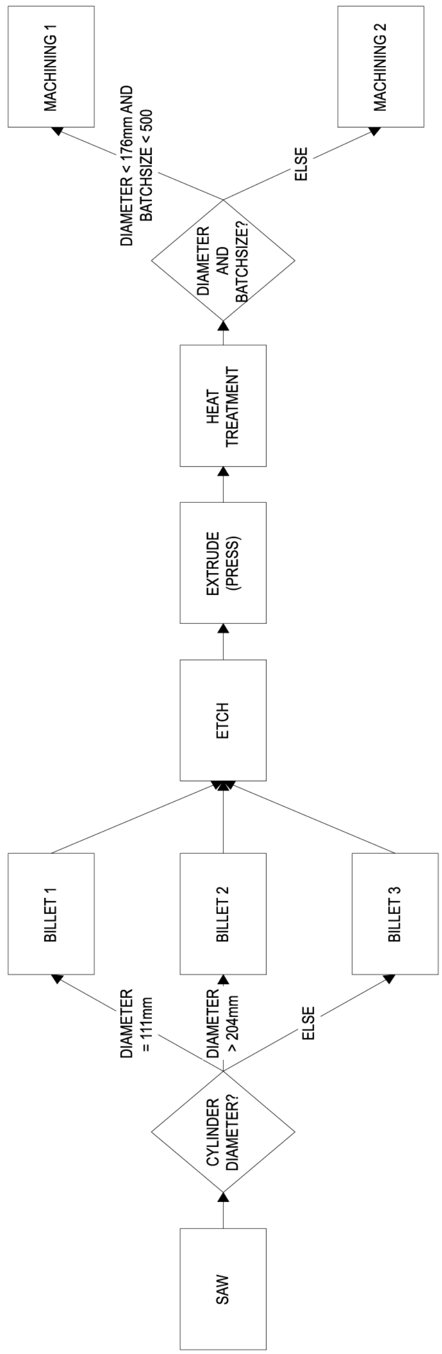


Figure 2.
Gas cylinder manufacturing process map

services sectors (Greasley and Barlow (1998)) which enables a model to be constructed by placing icons on the screen and sets parameters, such as process times, using dialog boxes. The simulation reads the cylinder data from a spreadsheet file. Various details such as cylinder size and machining production rates are saved as attributes and carried with the cylinder batch as it passes through the simulated production system. Each machine centre is a custom designed program block, built using the "Professional" version of the ARENA system. This allows the incorporation of a menu system within each work station icon, allowing for easy change of parameters such as machining rates and machine availability.

Verification and validation

Verification or code debugging was undertaken by extensive use of the simulation animation facilities to observe the behaviour of components within the system. The model was validated by observing performance measures for a cylinder sequence taken directly from the capacity plan. As in all simulation studies the level of detail is dependent on the study objectives. In this case, the aim was not to obtain lead time measurements and thus it was only necessary to model up to the machining stage.

Experimentation

The main objective of the simulation study was to investigate the use of production sequencing scenarios in the production planning process. The current method is to base the production sequence on the customer date and order quantity information held within the capacity plan. However, this had led to high levels of WIP, long production lead times and thus poor delivery performance. A change suggested by the company was to group together customer orders for either small or large cylinders (each customer tended to only order either small or large cylinder types) in order to reduce machine setup times when moving between cylinder diameters. Two versions of this approach were tested using the model. The "Small/Large" sequence using a large group size and the "Small/Large/Small/Large" sequence using a smaller group size. The final scenario tested was to divide the cylinder orders into packets of equal work content, with work content defined as the cylinder cycle time multiplied by the batch size at the extrusion press. The work content of each batch of cylinders was made equal by calculating the average work content for the order sequence and making each batch equal to this. The work was then "pulled" onto the production system using the extrusion press as the control point. The extrusion press was chosen as the control point as it was identified as the bottleneck process and should therefore, set the pace of production (Skrikanth and Cavallaro, 1993). The aim of this approach is to protect the bottleneck from unexpected problems by feeding it with sufficient work and an additional buffer amount.

Results

To investigate the effect of cylinder sequence on the cylinder production cycle time the simulation was run for an extended period until the model reached steady state behaviour. Table I shows the results for the current sequence, the two suggested sequences of alternating between small and large cylinders and the equal work content sequence described in the experimentation section.

It can be seen that the small/large sequence pattern performed better then the current sequence based on the capacity plan or the Small/Large/Small/Large mix. The improvement in cycle time is small (approx. 2.5 per cent) but would represent a significant increase in cylinder output over a year's production. However, using a sequence based on the "equal work content" principle improves system performance further, leading to a 5 per cent improvement over the current sequence. The approach attempts to provide a smooth workflow to the press by creating batches of equal work content. However, a drawback to this approach is the need to calculate the average work content figure and then derive a sequence of cylinder batches that match this figure. In this study, a spreadsheet was used to prepare the cylinder sequence. One further difficulty in this approach is the time lag between submitting new material to the production process at the saw process and it reaching the extrusion press. In order to minimise this time lag the control mechanism for feeding material into the system (i.e. the point at which the loading on the extrusion press was monitored) was placed at the etch, rather than the extrusion press itself, to eliminate the 1 day control delay which would occur while material is processed at the etch. The control mechanism could not be placed at the saw or billet process as different sizes of cylinder are processed on different work stations and so the timing of material reaching the press cannot be accurately determined. The simulation study confirmed that the equivalent of 1 day of WIP inventory could be eliminated from the production system by moving the control mechanism in this way.

The system dynamics study

Although the simulation was able to investigate the operational issues of the manufacturing process itself, a different approach was taken to tackle the wider problem of production planning disruption due to the order scheduling process. This would normally be treated as the "environment" around which the DES is based. SD (Forrester, 1961) (termed the fifth discipline by Senge (1990)) is an approach for seeing the structures that underlie complex situations and thus for identifying what causes patterns of behaviour. In an organizational setting, it is postulated that there are four levels of the systems view operating simultaneously, i.e. events, patterns of behaviour, underlying structures and mental models (Maani and Cavana 2000). Events are reports that only touch the surface of what has happened and offer just a snapshot of the situation. Patterns of behaviour look at how behaviour has changed over time. Underlying structures describe the interplay of the different factors that bring about the outcomes that we observe and mental models represent the beliefs, values and assumptions held by individuals and organizations that underlie the reasons for doings things the way we do them. This framework is now used to analyse the case study scenario.

Table I.
Sequence scenario results

Sequence scenario	Average cycle time (min)
Current sequence	16,256
Small/large	15,852
Small/large/small/large	16,328
Equal work content	15,415

Events

A recurring event was that of missing customer order dates. This was leading to dissatisfied customers and an increasing reliance on a few "strategic" customers who were using their buying power to negotiate price reductions and so reduce profitability.

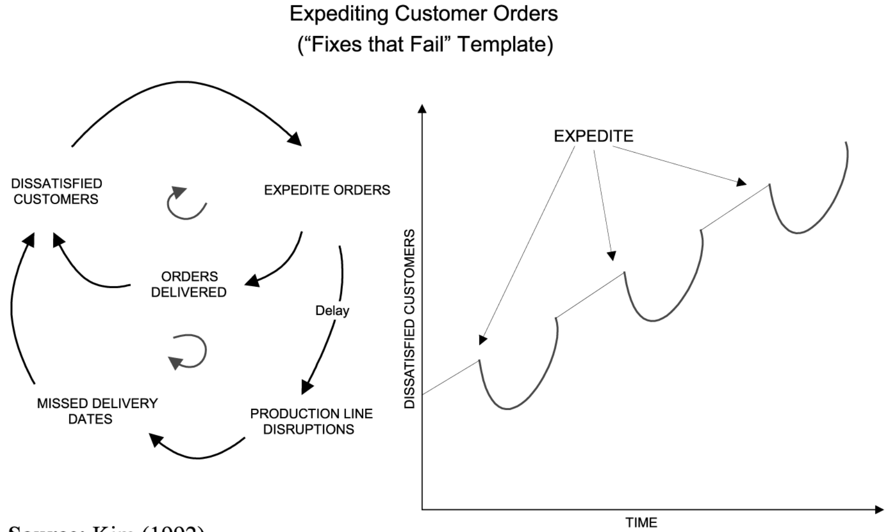
Patterns of behaviour

Orders are made to customer demand (i.e. not supplied from stock) and are placed on to the capacity plan over a number of months before the actual order is manufactured. The position of an order in the plan is a result of negotiations between the customer, the sales manager who liaises with the customer and a capacity planner. A senior manager is also involved for "strategic orders" which are deemed to be of particular importance to the company. There is no fixed definition of what makes an order "strategic". The production plan for an order is only fixed when the order enters the manufacturing process, approximately seven weeks before delivery to the customer. Because of the wide variety of products offered, the extended amount of time an order is on the capacity plan and the changing capacity situation lead to a great deal of uncertainty in the capacity planning process. In particular, the process of expediting "strategic" orders has led the company to be labelled by many "non-strategic" customers as unreliable in terms of delivery performance. This behaviour has increasingly led to some customers over-ordering or ordering in advance to ensure on-time delivery leading to a capacity plan which overstates the actual capacity requirements. Also, due to poor delivery performance some customers have chosen to move to alternative suppliers which has led to an increasing proportion of the output being dedicated to "strategic" customers. This has led to an even greater use of expediting as the "strategic" customers become an ever increasing proportion of the company's output.

Underlying structures

One of the tools of SD is system archetypes which are certain dynamics that recur in many different situations. An archetype consists of various combinations of balancing and reinforcing loops. The "fixes that fail" archetype (Kim, 1992) describes a situation in which a solution is quickly implemented that alleviates the symptom of the problem, but the unintended consequences of the "fix" exacerbate the problem. Over time the problem symptom returns to its previous level or becomes worse. An example of the "fixes that fail" archetype is that of "expediting customer orders" (Figure 3).

Figure 3 shows how, in an effort to ensure on-time delivery, an order is expedited resulting in a satisfied customer. However, the disruption caused by this policy has led to the need to expedite further orders and a feedback loop is established, where more expediting leads to disruptions, leading to missed delivery dates leading to dissatisfied customers and more expediting. The reason this situation occurs is that the pain of not doing something right away is often more real and immediate than the delayed negative effects. The situation is exacerbated by the fact that the reinforcing nature of unintended consequences ensures that tomorrow's problems will multiply faster than today's solutions. In other words solving one problem today, will not create another one tomorrow, but will create multiple problems. Breaking the archetype requires the acknowledgement that the fix is merely alleviating a symptom and making a commitment to solve the real problem now. In this case the idea of



Source: Kim (1992)

Figure 3.
Expediting customer orders systems archetype

"strategic" orders is creating a self-fulfilling prophecy in which eventually all orders will be "strategic". In this situation the company will supply to fewer and fewer customers, who if they realise their market power, can exert substantial pressure on prices and profit margins.

Mental models

This concerns the most "hidden" level of SD and concerns assumptions, beliefs, and values that people hold about the system. In order to investigate these issues which influence the accuracy of the demand forecast, a questionnaire was administered to 10 sales managers who provide the interface between the customer and the capacity plan. The questionnaire consists of a number of closed questions with space for open-ended comments after the answers. The results of the questionnaire are presented in Appendix A and a summary of outcomes is presented below codified into three themes.

Theme 1: Changes to the Order Specification (Questions 1-4) The sales managers report that customers request production space usually within a 12 months period. Some eight sales managers often request this production space in advance. Space is usually requested by medium to large size companies. Seven sales managers have experience of customers often or always changing the size and/or delivery date of the order. Up to 3 months notice is given for this and four sales managers report disruption to other orders when they do change the production schedule to accommodate this. As one sales manager explained:

> "Some of my customers tend to want their delivery postponing when cylinders are due out in 2 weeks time. By this time it is too late".

The reason for making these changes is clear in that eight sales managers report they gain orders from accommodating these changes whilst only two claim orders are lost.

One reason why customers may do this is that they have a misunderstanding about the production process, according to one sales manager:

> Some customers still believe cylinders to be "off the shelf".

Theme 2: Capacity Planning Rules (Questions 5-9) Nine sales managers always consult the capacity planner before quoting a delivery date and nine sales managers never or rarely are refused space by the capacity planner for the order. Only six sales managers understand the current capacity planning rules, and only five sales managers actually work to these rules. The following quotes underline the current misunderstanding of the capacity planning rules.

> Don't know if any hard fast rules exist.

> Rules changed three times since we started forecasting. Sometimes there is a lot of confusion about what is requested.

> Don't know of any rules. The larger customers tend to plan their requirements for the whole year.

Of the four sales managers who don't understand the rules all agree it would help them in their task if they did.

Theme 3: Priority Customers (Questions 10-11) All 10 sales managers have priority customers and nine sales managers often or always have priority orders scheduled. The need to satisfy "strategic" customers is underlined by the comment from one sales manager:

> Companies X, Y and Z more or less always get what they want.

In summary, from a customer perspective the late changing of orders is accepted as if it was part of the normal "trading" practices with the company. Poor delivery performance has "labelled" the company as unreliable. Consequently, the customers regard themselves as being in a strong bargaining position. Customers prefer to book in advance provisional orders as the lead-time is long. Some customers believe the company makes to stock which in reality has never happened. A feeling of confusion exists over the capacity planning rules. The effect of this is that rules are "made up" to suit the needs of the individual with the consequence that order quantities are over-booked, enquires and reservations are booked as "provisions" for their customers. Non-standard practices are accepted as normal as this enables some element of control over a system that is poorly understood. Finally a priority system operates in order to ensure what the sales managers consider are the most important customers receive on-time deliveries.

Senge (1990) states that most people assume cause and effect are close in time and space. Thus a fixation on short-term events will fail to uncover the longer term pattern of behaviour caused by their actions – in this case the longer term effect on scheduling stability of short-term expediting decisions. In order to break the cycle both the belief and assumptions about the planning process had to be addressed and an even greater understanding of the systemic structures was needed in order to understand the relationship between short-term fixes and a longer-term drop in performance. In order to achieve this, meetings were held with the sales managers and use was made of the archetype diagrams and the results of the questionnaire to discuss the effect of the current planning rules. As a result of these meetings the following policies were agreed:

- Quotes for delivery times to "strategic customers" would not disrupt the current production plan.
- Delivery times would be maintained and not brought forward if they caused disruption to the current production plan.
- Sales to liaise closely with manufacturing to gauge realistic delivery performance.
- Manufacturing to liaise closely with sales regarding up to date production schedule information.

Discussion

The case study has described a DES study of a production facility that provided suggestions for improvement in terms of production sequencing. As the project progressed it became clear that although the DES would meet the objectives of the study in a technical sense, the organizational problem of "delivery performance" would not be solved by the DES study alone. After a request by the author a wider brief to the project was agreed involving an assessment of the order scheduling process undertaken by the sales managers.

An SD approach is used to provide a framework for understanding why things are happening in the way they are by identifying the structure behind behaviour. This differs from the DES approach which generally replicates the structure and identifies behaviour under a number of scenarios. A SD approach involves identifying an archetype which describes the systemic structure of the system. It also assesses the underlying beliefs and assumptions of the participants. In this case, it was found that the SD approach provides the following advantages:

- Expands the DES model of the production system to a model that incorporates the role of decision makers, thus providing a deeper understanding of system behaviour and the reason for missed deliveries.
- Treats the cause of the production problem rather than the symptom. This led to a recognition of the relationship between missed deliveries and the actions of sales and production personnel.
- Demonstrates, using the system archetype, that a more long-term view of improvements following on from change was required rather than the "quick fix" solution of expediting orders.
- Shows the need for personnel to consider their own actions rather than blame others for outcomes. All participants in the sales and production process need to consider how their actions affect delivery performance for all customers.

Of interest in the case was how the DES study led to a wider analysis using SD. Initially in the case study the technique of DES was commissioned for a "hard" technical analysis of a production system. However, it has been noted that the DES technique can incorporate qualitative aspects in its analysis (Robinson, 2001; Swenseth *et al.* 2002). For example, the use of process maps and the visual animation display can provide a forum for discussion and understanding. This case discussion between participants regarding the organizational issues surrounding the production planning system, triggered by the DES study, led to an analysis using the SD technique. This analysis would be unlikely to have occurred without the DES study because the SD technique was unfamiliar to the organization and initially the problem was seen as a technical issue requiring a DES solution.

Thus it is argued that the qualitative outcomes of DES should be seen as an important part of the DES technique and the SD approach can provide a useful addition to the toolkit of DES practitioners.

However, there are limitations to both the DES and SD approaches which may warrant the use of further techniques. For example, although DES and SD can make some attempt to incorporate the views of participants they may not be able to grasp the complexity of social reality necessary to ensure a correct analysis is made. Further, "systems approaches" such as Soft Systems Methodology (Checkland, 1981) may be needed in such situations (Jackson, 2003).

Conclusion

The study has shown how DES modelling can assist in the analysis of a manufacturing system by investigating changes to production sequencing rules. It is proposed that the technique of DES can be complemented by the use of a SD approach to analyse policy decisions which impact on the system being investigated. The SD approach aims to explore deeper than the surface events, establishing patterns of behaviour, the underlying systemic structures and the mental models of the participants. This makes it particularly appropriate in analysing factors impacting on the organizational context of the DES study.

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Appendix

1. How far in advance do your customers request production space?

1-3 months	8
4-6 months	9
7-12 months	7
+12 months	1

2. How often do your customers request advanced production space?

Never	0
Rarely	2
Often	6
Always	2

3. On average, what type of customers request advanced production space?

Small	1
Medium	9
Large	8

4a. Do your customers change the size/delivery date of the order?

Never	0
Rarely	3
Often	6
Always	1

4b. How much notice do they give of these changes?

1 month or less	8
1-3 months	7
4-6 months	2
7-12 months	0
+12 months	0

4c. Do these changes disrupt the provisions for other orders?

Yes	4
No	6

4d. Have you ever lost other orders due to accommodating changes?

Yes	2
No	8

4e. Have you ever gained orders due to accommodating changes?

Yes	8
No	2

5. Do you consult the capacity planner before offering the customer a production space?

Never	0
Rarely	0
Often	1
Always	9

Figure A1. Results of questionnaire to ten sales managers

6. How often are you refused advanced production space from the capacity planner?

Never	2
Rarely	7
Often	1
Always	0

7. Do you understand the current capacity planning rules?

Yes	6
No	4

8. Do you always work to these rules?

Yes	5
No	5

9. If you answered no to Q7, would it help you if you understood the rules?

Yes	4
No	0

10. Do you have any priority customers?

Yes	10
No	0

11. How often do you have "priority" orders?

Never	0
Rarely	1
Often	6
Always	3

Figure A1.