Paper II

Improved efficiency with production disturbance reduction in manufacturing systems based on discrete-event simulation

Arne Ingemansson, Gunnar Bolmsjö

Department of Mechanical Engineering
Lund University
Box 118, SE-221 00 Lund, SWEDEN

Published in:
Journal of Manufacturing Technology Management
Volume 15 Issue 4
2004

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Arne Ingemansson, Gunnar Bolmsjö

Department of Mechanical Engineering
Lund University
Box 118, SE-221 00 Lund, SWEDEN

Abstract

Discrete-event simulation (DES) and disturbance reduction techniques are a combination for improving efficiency in manufacturing systems. The DES modelling allows different tests to be carried out by step by step alteration. The use of manufacturing improvement techniques should be combined for best results. The changes in disturbances will show us different alternatives in output of the manufacturing system. Two case studies have been accomplished to study the possibilities for disturbance reduction in manufacturing systems by using DES with the proposed method for improved overall manufacturing efficiency. The case studies showed an improvement of output 14% and 18%, respectively.

Keywords

Discrete-Event Simulation, Manufacturing Systems, Production Disturbances, Reliability, Productivity Improvement

1 Introduction

An increased productivity and better overall efficiency of the manufacturing lines are important goals for many companies. Handling of disturbances is of great importance for more reliable and robust manufacturing systems. Disturbances can occur in all system levels in manufacturing and it is important to achieve a more systematic approach to increase overall productivity for a system. The issue of disturbances in manufacturing lines is a common industrial problem (Smet, Gelders

& Pintelon, 1997). There is also potential to increase production when previous research show that of total production time only 50-60% is used for manufacturing and the rest of the time is wasted in different disturbances according to studies (Ericsson, 1997; Drucker, 1990; Viktorsson, 1989). With ever-increasing global competition, the total efficiency of a manufacturing system is of vital importance.

DES is a tool suitable for analysis of the dynamics of discrete processes such as manufacturing systems. Important aspects on applying DES in analysis of manufacturing systems include effect on product changes, changes in the system itself, possibility to compress time so different scenarios can be analysed in a short time (Banks, 1998). There is need for new ideas in the area of disturbance reduction to increase overall efficiency and the combination of DES may be one. More ideas for improvement both regarding machine equipment and human involvement in disturbance handling seem necessary to achieve an increased overall productivity.

The goal of the study is to introduce a methodology based on DES for reducing disturbances in manufacturing systems. Another aspect is to make both the academic and industrial areas more aware of the importance of disturbance reduction. Manufacturing systems tend to become more and more complex and there is a need to take a more scientific approach to the background causes to why production disturbances occur in a system. DES is a powerful tool to analyse disturbances, their effects and propagation in a manufacturing system due to the easiness of alterations in a model and improvement in the system can easily be shown.

2 Production Disturbances in Manufacturing Systems

Disturbances can occur in different parts of a manufacturing system. A production disturbance is an unplanned or undesirable state or function of the system (Kuivanen, 1996). Disturbance elimination consists of all the measures taken to restore the system to a planned or desirable state. In this study all the disturbances are related to the actual manufacturing system of the products. Another approach is to classify mainly "equipment failure" and idling and minor stoppages (Smet et al., 1997). The definition of production disturbances is not yet homogeneous. Many aspects can be included, but the most important is to see the possibilities of disturbance reduction.

To describe the efficiency of a manufacturing line the production disturbances can be classified in downtime, speed and quality losses. Downtime losses can further be divided into planned and unplanned stops, see Figure 1. Different examples are shown to each category in the picture. Downtime losses are seen as the most

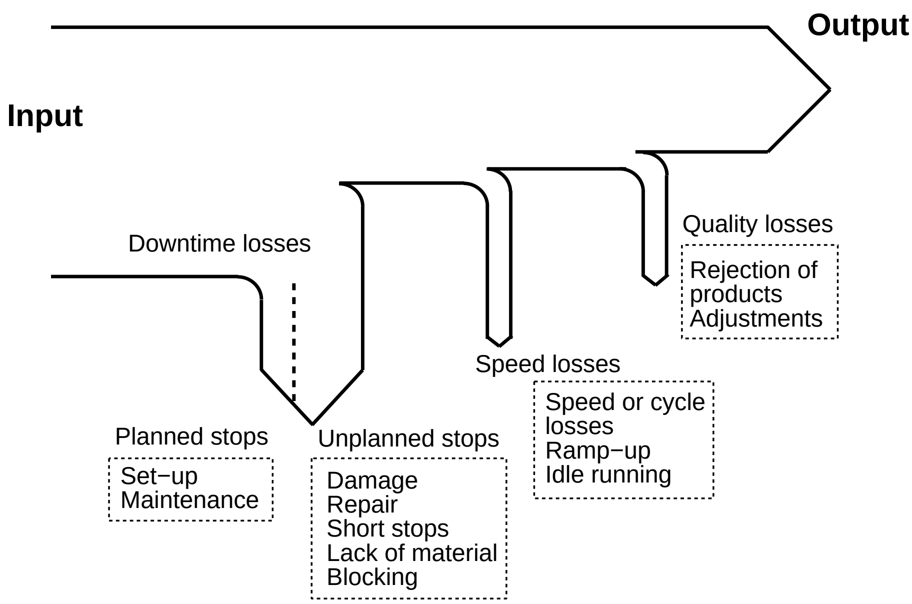

Figure 1: *Different disturbances categorised. To reduce downtime losses are in most cases the best way to increase efficiency of a manufacturing system.*

important to reduce to increase overall efficiency of a system. To describe when the system is down the parameter is DT and TBDT is used when the system is working at normal state.

The disturbances can cause blocking which means that the next machine in the process can no longer deliver their material. The other case is idleness where the machine runs out of new raw material. In linked lines the disturbances often propagate throughout the line. The focus is on the actual manufacturing process but in real life there are also other issues related to the production process depending on supplier, planning etc. The concept of production responsiveness (Matson & McFarlane, 1999) refers to the ability of a production system in terms of its operational goals in the presence of supplier, internal and customer disturbances. Disturbances are those sources of change, which occur independently of the system's intentions. This is an interesting approach but according to the author severe to implement in a simulation model. A first issue is to take care of disturbances within the manufacturing system, as the potential is substantial. In a wider perspective these issues regarding internal and external customers may be included if the simulation model is further expanded.

Different methods to estimate the reliability of manufacturing systems exist. A field survey of the causes and effects in two countries showed that more than one third of the production disturbances were caused by system designed errors (Järvinen, Vannas, Mattila & Karwowski, 1996). Another study suggested a model based on failure due to random shock loads together with a strategy for preventing or minimising such failure at optimum cost (Mathew & Kennedy, 2002).

The human behaviour in a manufacturing system is also important to consider. The time of a manual operation and the behaviour of the operator are important factors to include. The human interaction is almost always necessary to solve production disturbances. It is difficult to put a number on human processing capacity limits for at least three reasons: equipment design, expertise and working methods available (Bainbridge, 1997). As a person becomes more expert they have developed a skill in the subject.

3 Analysing Disturbances with DES

There is a need to apply a more multidisciplinary approach of the design regarding the manufacturing systems. The structure of many manufacturing systems, designed with lack of flexibility and other discrepancies, does not work with the rapid technological change and challenging market demand (Wu, 1994). Often there are little or no differences in the products put on the market by competitors which results in product price and time to market are important variables to achieve success for a company. Thus, manufacturing systems that are able to address these issues put a company in a competitive advantage.

Different manufacturing strategies and improvement techniques have been studied. The best parts of TPS are considered to be adopted for efficiency of a manufacturing system. Lean production has proved to be successful since it points out those who actually are adding value to a product. The interaction between human and machine is also vital for a system (Harlin & Ylipää, 1999). Designer errors of a manufacturing system can be a major source of operating problems. The more advanced a control system is, the more crucial the contribution of the human operator will be. Furthermore, the designer who tries to eliminate the operator leaves the person to do the tasks that the designer cannot think how to automate (Bainbridge, 1983). The organisational part should not by any means be neglected for a high performance manufacturing system. It is important to measure the performance and compare it to other similar systems to achieve an increased overall efficiency. Other improvement techniques that can be mentioned are supply chain management, TPM and SMED (Single-Minute Exchange of Die).

There is always a problem to estimate the accuracy of the model and especially if the model is describing a non-existing equipment or line. The model is an abstraction of reality and perfect representation of it could never be expected (Banks, Carson & Nelson, 1996). There is also a correlation between the accuracy of the model and time spent on it. Therefore, the accuracy of the model must be evaluated in the simulation model to obtain realistic results. There is a limit when improvement on the model is not worth the cost and the limit varies from simulation case to simulation case and it could be useful to evaluate how effective time is spent. A taxonomy that classifies the verification, validation, and testing techniques has been suggested by Balci (1998), many of those performed instinctively when building the model. Incremental development of a simulation model might be an alternative. A smaller model could be expanded or improved in different steps, which also is a way to reduce overall risk in a project (Randell, Holst & Bolmsjö, 1999).

It is necessary to be aware of the connection between the different tools for improvement of production systems and DES to improve a manufacturing system. Unfortunately today simulation is not often integrated in the development process. In a best case scenario the simulation model should be a “virtual copy” of the real manufacturing system (Klingstam, 1999). The production tools are based on improved techniques widely used and successfully implemented all over the world. The system can be showed before and after alterations without expensive modifications in real-world scenarios.

4 Industrial Case Studies

The case studies have been accomplished in order to study the possibilities for disturbance reduction in manufacturing systems by using DES combined with the goal of implementing improved overall manufacturing efficiency. The two case studies described are used to increase efficiency of the manufacturing systems. One of the companies has adopted the DES concept more broadly whereas the other is in a more initial phase. The companies were chosen as they actively work with production disturbance reduction and are judged to benefit from applying DES to increase the efficiency of the manufacturing lines.

4.1 Case Study no. 1

The company in case study no. 1 produces equipment and machines to the window blind industry. The production unit in Sweden employs some 100 people. The company has a wide range of products in the product mix including both ma-

Table 1: *Initial background data to case study no. 1.*

Cause of production disturbance	Number of stops, weekly average per machine	Estimated DT per stop (minutes)	DT per week (minutes)
Full bobbin	1.3	5	6.4
Yarn empty	0.9	30	27.0
Yarn breakage	0.4	2	0.9
Core thread empty	0.3	5	1.5
Miscellaneous	-	-	-
Sum DT			35.8

chines and consumer goods. The studied product, braided cords, is produced in 72 different machines and each of the machines has two units making two cords independently. The machines operate 24 hours a day, 7 days a week and they operate unmanned as long as no disturbance occur, up to some 100 hours. About 60% of the cords manufactured were coloured in a separate colour machine. As a final operation, both coloured and white cords are sales packaged before transportation to storage.

The manning was two operators daytime. Some experiments were carried out to change manning in real life but it was considered by the company as too expensive to have personnel at two shifts or more. Thus, more manning and more shifts may increase the overall capacity of the system. This option is not the most cost effective. However, try-outs were suggested with personnel to be on shorter duty on week-ends. Those simulations are not included in the case studied.

The system in current use for disturbance gathering was a manual log-book. The historical data available were causes of production disturbances logged in different categories. Disturbance data were logged only as reason in five different classes and the actual time involved to take measures to reach normal production was not included, see Table 1 for a weekly average for a measurement period of 26 weeks. The DT was only estimated as the time for action and not including the time for WT. DT was on average only 35.8 minutes per week for each machine. The values were too short and it did not match with current production rate. Additional measurements were necessary.

To receive more relevant disturbance data for the DES model, two vibration indicators with time logging were placed on two different braiding machines. The indicators logged a clock-time table for DT and TBDT for 6 weeks. The operators then manually added the different causes why the machines had stopped. See Table 2 for a summary of the measurements. The weekly average DT increased

Table 2: *Data from measurement of vibration indicators, case study no. 1.*

Cause of production disturbance	Number of measured stops, weekly average per machine	Measured minimum DT per stop (hrs:min)	Measured maximum DT per stop (hrs:min)	Measured DT weekly average per machine (hrs:min)
Full bobbin	1.1	00:05	14:48	08:19
Yarn empty	1.1	00:41	52:38	27:26
Yarn breakage	0.5	00:01	107:35	14:15
Core thread empty	0.3	00:01	01:30	00:10
Miscellaneous	0.7	00:01	45:34	04:27
Sum DT				54:37

from 36 minutes to 54 hours and 37 minutes. The WT changed the values considerable.

The MRP (Manufacturing Resource Planning) system indicated some rough data on annually basis but unfortunately not adequate for simulation input. The data could, however, be used for later validation of relevance of the model. All values were compared to annual production data logged in the MRP-system. The model was simulated in steady-state mode.

A main source for input data was interviews with the personnel. It was possible to recognise their working methods and obtain some solid times for the different activities. Frequent maintenance problems and times for repairs with some parts of the equipment were also raised with the maintenance staff. A simulation model was built of the studied production unit, see Figure 2. Selected bottlenecks, such as the braiding department and the colour machine in the system, were magnified in separate models for further experiments.

Production disturbance reduction

Production disturbances due to very long waiting times before any actions were taken to get the system back to normal state were considered to be most important to reduce. This was found especially around the braiding machines and also in the station where the threads were coloured. In the area of the 72 braiding machines the waiting times were more than 90% of the total DT. Tests were carried out with new working schedules for the personnel to improve the output. To show the status of the machines “Andon” were also suggested. “Andon” is signal signs for easy check of the status of the machines, e.g. working or not working.

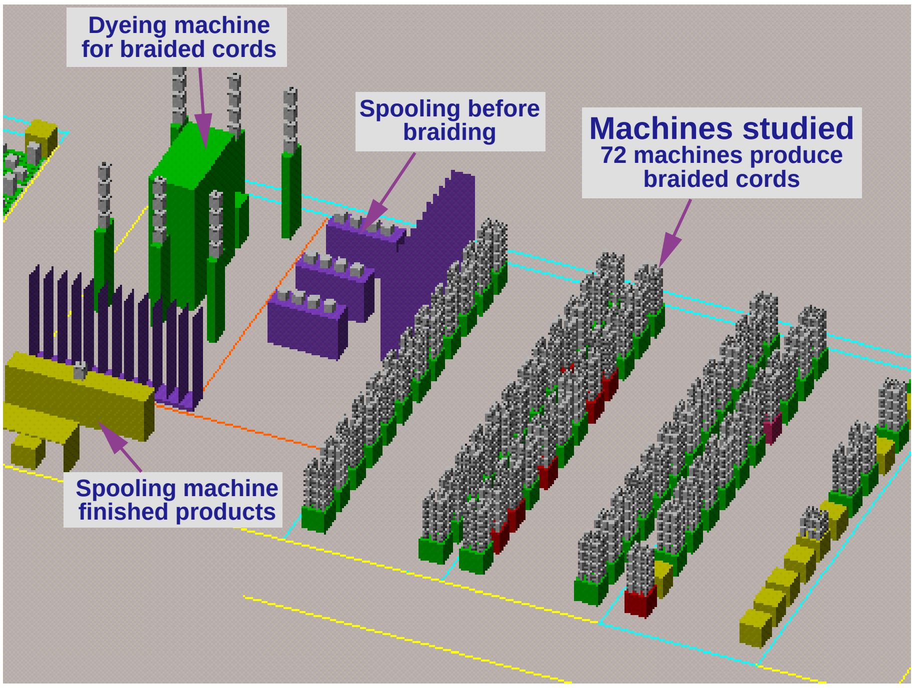

Figure 2: *Layout of case study no. 1. Experiments were carried out with parallel set-up of two machines simultaneously in the section to the right with 72 machines.*

The DES working method made it possible to see what was changed when one disturbance was removed. One cause of disturbance was deleted in the simulation model and the simulation model was then tested again. The results were also confirmed in real-life tests. When parallel changing was introduced it showed an improvement of 18% of the time available for production. The working method showed a good correlation between the model and the real system, the deviation estimated by the author to less than 10%.

The colour machine had a long set-up time, approximately two hours. This combined with the overall demand for the company of reduced lot sizes made it interesting to work with set-up reduction. If the set-up time was reduced by 50% to one hour instead of two hours, the corresponding lot size could be reduced by half with equal total output and comprising much smoother production flow. The company goal to reduce WIP (Work In Progress) also co-operates with the proposal suggested.

Results and conclusions

A conclusion of case study no. 1 was the ability to increase output with non-expensive means. The potential was proven in the DES model before it was implemented in the manufacturing line. A change in work order, parallel changing of two machines at the same time, improved the results. The importance of the operator's knowledge was also a key issue. Interviews with the operators at the manufacturing cell gave valuable information. The current system for collecting production disturbances was suggested to be replaced with a more active system. The vibration indicators enabled real-time measurement. The case study showed that by easy means, e.g. different working routines and preventive maintenance, improvements could be made with cost-effective means. The potential in the case study to increase output was shown to be 18%, which is a considerable advantage on the use of existing machines and equipment. An effect of this study was beside the actual simulation model that issues around the manufacturing line were raised and discussed.

4.2 Case Study no. 2

The company in case study no. 2 manufactures forklift trucks for warehouses. The company has been expanding in volume during a longer period and at the same time with continuous growth in profit. Investments in new production equipment have been extensive to keep pace with increased production output. Production is based on customer orders with flexible manufacturing techniques. The components produced in the studied cell of the case study consisted of two main articles of frames. The fabrication of these frames was divided into some standard lengths and many customised lengths. The system is operating 24 hours a day, 5 days a week and also on two shifts on the weekend. The potential to increase working hours is limited mainly due to the costs with more shifts. Time must also be allocated on the week-ends for example preventive maintenance. This means higher production by increased manning is limited.

The model was partly imported from a larger model previously built at the company. The manufacturing cell was identified as a bottleneck in the overall system studied. The model was updated and modified with alterations included in the station to get it to work like the current existing real-world system. Input data, automatically logged from the PLC system were not adequate for disturbance studies. Only breakdowns and stops more than 15 minutes were logged in this system and all minor stops were missing.

Manual logging was carried out by the author during a week to observe production

Table 3: *Measured data in case study no. 2.*

Cause of production disturbance	Number of measured stops, weekly average	Measured minimum DT per stop (hrs:min)	Measured maximum DT per stop (hrs:min)
On-line programming	4	00:51	02:42
Waiting	21	00:01	00:42
Welding process	16	00:01	00:27
Miscellaneous	6	00:01	00:16

disturbances and to obtain a thorough overall view of the system. The manually logged data combined with interviews were the basis for input data modelling. See Table 3 for an overview of the measured data. The layout of the model is illustrated in Figure 3. The average tact time per frame is 34.3 minutes when the measurement started. To indicate the potential with the case study, in an idealistic state with no disturbances at all the tact time should be as low as 17.0 minutes per frame.

Production disturbance reduction

Different proposals in various areas were suggested to the company to improve the productivity of the station. The model showed that the main production disturbances were concentrated to a combination of long downtime disturbances and also shorter ones related to the welding process. As shown in the previous case study another potential can be achieved by changed organisation and improved preventive maintenance. For example was a new routine established to always have a queue of tacked frames in front of the robot cell. The idle time of robots could by then be reduced. The outcome of increased productivity is so significant that it may delay investments in new production equipment.

The main ideas to be implemented in the studied cell were: off-line programming of the station, all on-line programming moved from planned production time or changed preferably to off-line programming; an increased use of unmanned production; and implementation of TPM in the welding process. The system directly showed an improvement of the time available for production and smoother production flow when on-line programming was removed.

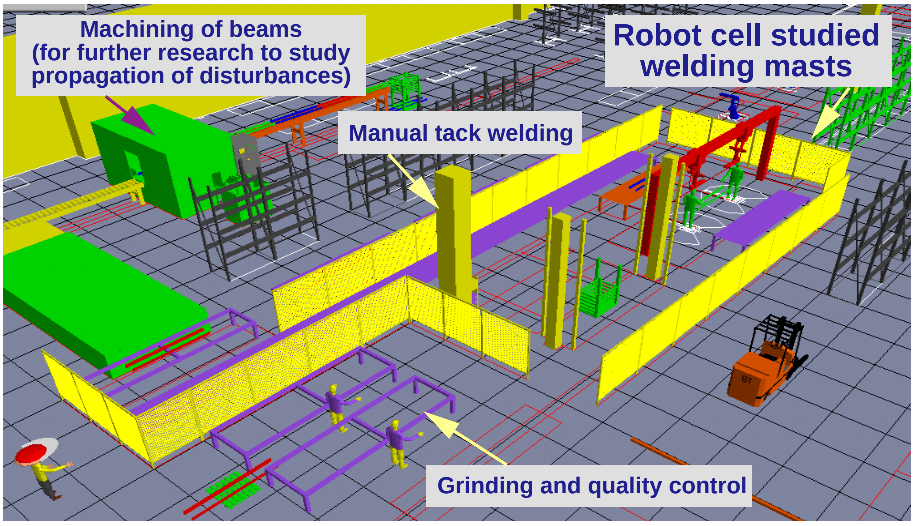

Figure 3: *Layout of case study no. 2. The efficiency of the studied robot cell was improved. Both longer (online programming) and shorter disturbances (due to the welding process) were reduced.*

Results and conclusions

The DES model in case study no. 2 showed that the key issue was to increase the use of the robots in the welding cell. It was the main bottleneck in the station during the step by step alteration phase in the DES model. There should always be a queue of tack welded frames in front of the station. In the most advantageous case there should be a finished tacked frame on each buffer ready for further transportation to the buffer in front of the robots for immediate action. To release the operators working load around the station some additional buffers may be added.

On-line programming is time consuming and disturbs the cell as well as other functions linked in the production chain. The interrupts propagate further down in the manufacturing chain, e.g. painting and assembly. If off-line programming is introduced, a new human resource, off-line programmer has to be allocated to handle the new system. This new resource allocated should be included in the overall cost of the station. However, this should be compared to the savings due to the current on-line programming in a cost-benefit analysis. The cost effectiveness of the new resource will in this case be considerable.

Principal result from case study no. 2 was an improvement of 14% of time available for production which was verified in shop floor tests. The tests showed a correlation between the DES model and the real system, the deviation approximated by the author to less than 10%. The most important conclusions from both case studies are to consider the long waiting times. The waiting times appear before action is taken to remove the actual cause of the disturbance. The best measure is to eliminate the disturbance and the second best is if the disturbance still occurs, to keep waiting times to a minimum. Another problem to consider when a disturbance has occurred is the way back to a normal state. There may be quality problems and also risk for new production disturbances during the ramp up phase especially for the welding process.

5 A Method for Production Disturbance Reduction

5.1 Steps in a Simulation Study

One of the most well-known descriptions of a DES study is introduced by Banks et al. (1996). The comprehended steps are described in this section, see Figure 4.

Identify system suitable for DES. The first step is to identify a system suitable for DES with dynamic variations or complex interactions. If the system is not appropriate to be solved by DES the case should therefore be transferred to be settled by easier means. Another angle is the cost and benefit analysis. If the cost for the study exceeds the expected long-term results a simulation study is not the correct approach.

Input data collection - conceptual model. The conceptual model describes all necessary parameters needed in the simulation model. It will also gain the actual model building. Advantages seen with the working method are that is easy to revert back and check all background data either when the model is built or at a later stage when the model is revised. It is considered to be normal to revise the model in several stages.

DES modelling. When the conceptual model is concluded the modelling phase of the system starts in the DES program. Verification and validation of the model are also important steps to take under consideration for a reliable output. If the input parameters and logical structure of the model are included, verification has been completed.

Result Analysis. Experimental design is carried out for different alterations in the model. A thorough testing period and sufficient number of tests of each scenario is recommended. An output analysis is also suggested. The results and their confidence intervals assure the exactness of the model provided that the input data and the different connections in the model are correct.

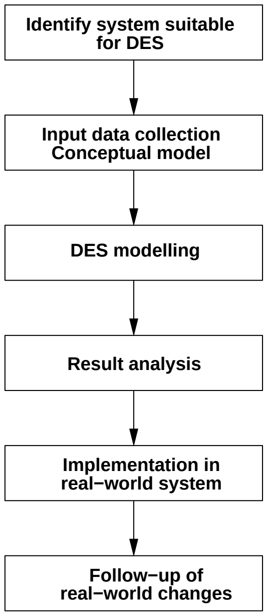

Figure 4: *Process of a DES of a manufacturing system project according to Banks, 1996.*

Implementation in real-world system. When all meaningful output data have been examined, an output result analysis can be concluded for implementation in a real-world system. The success of implementation in the real-world systems depends on how well previous steps have been performed.

Follow-up of real-world changes. As a final step in Figure 4, the implemented changes in the manufacturing system are monitored to see if intended results are fulfilled. This is also feedback to future models built in DES. The length of the monitoring phase can be discussed, but the longer the better. The changes in a steady-state manufacturing system are stabilised in the system after some time depending on which system studied.

5.2 Definition of the Methodology

Disturbance reduction in a system can be comprehended in different steps in a simulation case, see Figure 5. There are three main functions included in the method: First, in the beginning there are the data necessary to study for the causes of disturbances in manufacturing systems. Second, in the modelling and result analysis phases there are the tests of different alternatives to detect the differences

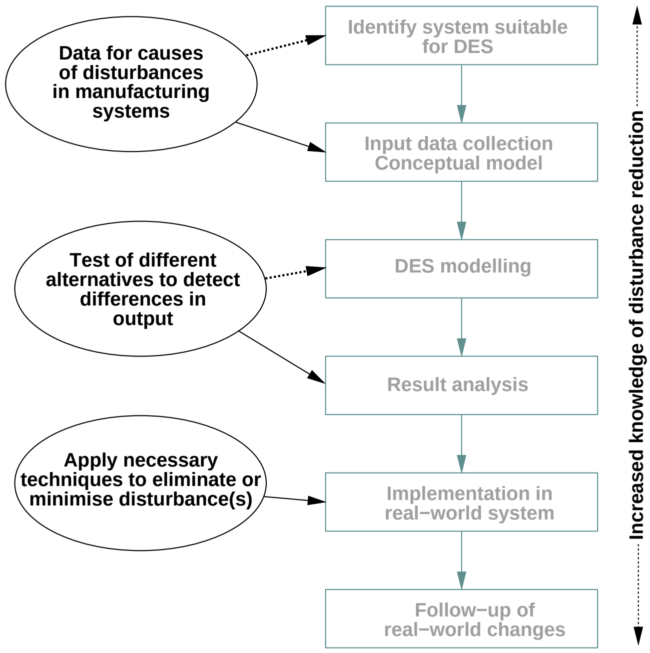

Figure 5: *Method of reduction of disturbances by using DES. Three main functions are combined with the DES process. An overall effect is the increased knowledge of disturbance reduction in the organisation.*

in output. Last, in the implementation in real-world phase of the model it is vital to apply necessary techniques to eliminate or minimise disturbances. This is all combined with continuous loop of improvement to keep the method up-to-date.

Data for causes of disturbances in manufacturing systems

The first important issue, see Figure 5, is the background data. In the input data collection phase different reasons and backgrounds for problems with the manufacturing systems are in many cases brought up for discussion by different groups in the organisation. Experience from field studies by the author shows that awareness of disturbances is not satisfactory in many companies. At the same time as input data are collected there is an educational phase to explain the different causes of disturbances. A discussion in co-operation with all involved parties can, before the simulation is built, show a significant improvement of overall productivity of the system. If the total efficiency of a manufacturing system is to be increased the training of the staff in several steps are to be included. The training may include bottleneck analysis, the value of implementation of TPM, smoother production flow among other things. The increased knowledge of the staff will itself be a valuable element in the overall improvement of the manufacturing system.

An important factor to take under consideration is the error in measurement of input data. If there is a lack of input data there is often a need for additional manual data collection. Collection of manual data has the advantage that one learns a great deal of the actual manufacturing process, the behaviour of disturbances and at the same time obtains many ideas how to improve the system. The disadvantage is that normal working routines can be affected in and around the manufacturing cell by the observer. As shown in the case studies waiting time is a considerable amount of the downtime of a process. Sometimes the operators prioritise the machines differently when a manual study occurs and the waiting times are reduced.

Test of different alternatives to detect differences in output

The second ellipse in Figure 5 is about tests in the DES model. The consequences of different alternatives and the availability to delete one or several disturbances could be easily altered in the model. This makes it advantageous to combine disturbance reduction studies and DES. It is important to simulate different scenarios with alternative variables after validation and verification and document these as a subject for discussion for alterations with related personnel for later changes in the real-world scenario.

Either one or several groups of disturbances can be deleted and the increase in output can be measured. The cost of decreasing disturbances should also be taken into account during the experiments. In many cases, as shown in the presented case studies, non-expensive measures can be taken with good results.

Apply necessary techniques to eliminate or minimise disturbance(s)

The amount of disturbances has to be reduced in the real world too. It is suggested to change one thing at a time. Some alterations could cause unwanted problems. If the changes are implemented slowly there is always a possibility to revert back one step. When changes in the manufacturing system are implemented it is also suggested to increase monitoring to see the actual system's behaviour.

The system with step by step alteration was also used in the industrial case studies presented. It proved to be a good way to follow the changes that affected the output of the manufacturing system. With this method it was also easy to see and understand changes of total output as well as different working conditions for the staff. It was also shown in the case studies that incremental changes of the system were a successful way of knowing what adjustments that were actually made.

Increased knowledge of disturbance reduction

Increased knowledge of disturbance reduction is also included in the process, see Figure 5. Parallel with all other activities there is the teaching and training phase. The new knowledge of the staff related to the manufacturing system could itself provide good results. An important overall effect when working with the method is the increased knowledge of disturbance reduction. The organisation is more aware of the concept of disturbance reduction. Often there is a new awareness of the efficiency of manufacturing systems.

5.3 Continuous Improvement of the Method

The continuous improvement loop of the model is also shown in Figure 6. The implementation of changes according to results in the model will lead to the manufacturing systems to react in a different way and with improved efficiency. Experiences from implemented results need to be fed back into the system both regarding disturbance reduction in real life and simulation building suitable for the working method both of how to implement alterations in a system and in the discrete-event simulation build-up phase. The manufacturing system itself can also be improved, for example when a new system is purchased, if the knowledge of disturbance reduction is increased.

Developing manufacturing systems is a complex task in itself. Therefore it is of importance to keep up with the latest development. Automatic disturbance logging seems in the longer run to be incorporated in the PLC system. This may facilitate the input data collection phase if the disturbance data are classified in relevant categories from the beginning. There are some ongoing projects by the author at Swedish companies that connect PLC system and DES, which will be further evaluated.

5.4 Experiences from Case Studies

The two case studies presented were performed with the actual method in mind and the results from the case studies showed an improvement in output of 14-18% within reasonable significance. This indicates that the combination of DES and disturbance reduction is suitable and will result in improvement of productivity.

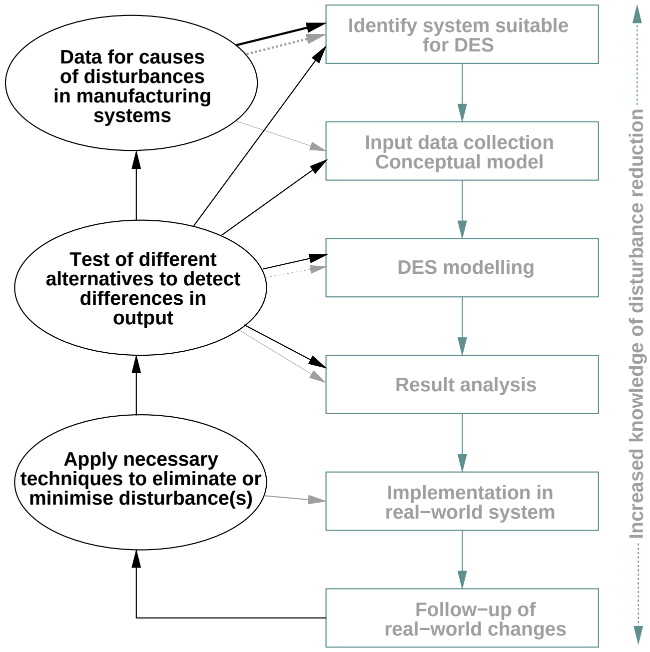

Figure 6: *Experiences from disturbance reduction and DES model building from implemented results need to be fed back into the system for continuous improvement of the suggested method.*

There are always uncertainties and the figures should be used as estimation. The results depend on various issues such as input data collection, model building, model measurement and implementation in the real-world system.

There are different alternatives to evaluate when disturbances are completely removed, reduced or changed to detect differences in output. The results from the model are then implemented in the real manufacturing system. Changes are made in small steps to see the dynamic effects of the alterations in the system. An important issue is the feedback loop that facilitates a continuous improvement of the model. New findings mainly in the real-world manufacturing system are reverted back in the DES modelling environment to achieve best possible results.

The step by step alteration technique presented proved to be useful. Most important are the problems regarding input data. In a case study, companies often have a tendency to think they already have all relevant input data readily available. The fact is that there is often a data collecting system available but seldom the data are adequate enough for direct input in the simulation model. Some data can be used supplemented with manual data gathering. The manual data gathering is time consuming but have advantages as well. It is an opportunity to learn more about the studied system and give input to the analysis as well.

Other issues to take under consideration are the staff's experience to implement the relevant working conditions in the model. Estimated data are in most cases inevitable and the know-how of the personnel is invaluable. Verification and validation and output data analysis have helped to achieve the best possible model and results. The DES projects have been simulated in steady-state simulation environment as the case studies work with the same products over a longer period.

6 Discussion

The objective of the study was to find and use a suitable method for disturbance reduction in a general manufacturing system. The potential of reduced cost is substantial when working with increased overall efficiency due to reduced production disturbances. There is a constant need for a company to improve profitability in a competitive international environment. A combination of a DES scenario and the real-life implementation makes it possible to achieve increased efficiency in a manufacturing system. The idea behind the proposed methodology is to have a useful technique and to apply it in a real-world scenario. The simulation program enables different experiments in production disturbance reduction in an excellent way.

Advantages with this proposed working method of disturbance reduction in a manufacturing system combined with DES could be mentioned as an efficient way of taking control over the system. The issue of documenting and follow-up of relevant data from the manufacturing system now and in the future is also raised. The manufacturing cell will bring up knowledge of the availability of the manufacturing system, documentation of production disturbances and explanation of the background reasons of why different disturbances occur in the system.

The outcomes of the case studies showed the potential for improvement in manufacturing systems. Different work order, without any new major investments, made it possible to increase performance of both case studies significantly. The results of the case studies and their accuracy can be further discussed. For the simulation model the output is dependent on the input data required. The measurement itself of input data on the shop-floor affects the values. Especially in case study no. 2 with manual measurement by the author, it was possible to see a production increase during the measurement period. It is suggested to minimize these errors in case studies with automatic input data collection.

The input data collected were tested in chi-square tests for assessing relevant distributions. Both in-house calculations and commercial software were used. The different distributional assumptions were rejected in both case studies and the method of empirical distribution was chosen for the different categories of production disturbances in the DES models. Practical experience shows the difficulty to transform measured values to distributions. The lengths of simulation runs were one year or longer to achieve best possible precision. The comparison of the DES models to the annual production data shoved a deviation of less than 5% in the DES models.

In the DES models a simulation output analysis was carried out. One of the main points with the performed case studies is the improvements in the models were implemented in real-life. The improvements should by no means be considered as exact values, rather an indication of the potential. The figures mentioned are approximate and the end results according to the authors' estimation may be deviating less than 10% in both case studies. However, the potential is shown to be considerable for production improvement.

Important issues to take under consideration are when working with this method: The time consumed of a simulation project is often underestimated. With parallel activities some time can be saved but if one single piece of input data is missing the model is inadequate to draw any relevant conclusions from. Input data are seldom directly accessible in a simulation study. The last missing data are often the most hard to obtain. In many cases approximations have to be used, e.g. maximum and minimum values. In real-world case studies time and cost are the determinant factors. Measures for improvement of manufacturing systems have to be taken in a short period of time and can in some cases be vital for a company's future existence. Quality of the DES model should, however, not suffer any loss due to lack of time or money.

An important issue to consider is the transformation of events from reality as input to the simulation model and how such events should be represented. Every data record measured must be included and issues such as disturbances are seldom fully considered. It is regarded to be extremely important to cross-check input data. The output data as a result from the simulation is directly linked to the input data. If not enough relevant data is put in the simulation model from the beginning, relevant output data are not obtained from the simulation model either.

Target group for application of the proposed method is production engineers. Today's DES software indicates, however, that it is more or less necessary to work continuously with the program to benefit from the features included. This is easier achieved in larger companies where a specific resource can be allocated.

DES software should benefit if applied with a better user interface.

In the simulation model the system is illustrated in a way that all personnel can understand, without any comprehensive background knowledge of production systems and other techniques, of the actual building and function of the model. The easiness to change different parameters such as the different disturbances is a powerful feature. Within a short notice after the change the results can be shown. A long period of time can be compressed and the dynamic propagation of disturbances can be shown not only in one but several cells or even as far as in a whole company or even further in a longer supply chain.

7 Conclusions

The method described showed an increase of overall output in two industrial case studies of 14% and 18% and is shortly described as follows: When all relevant input data are collected, tests of different alternatives can be implemented to detect changes in output. Based on the experiments and results from the simulation models, necessary measures to minimise or even eliminate disturbances can be carried out and increase overall efficiency. The implementation in the real world is based on the results in the simulation model. Changes in the real world manufacturing system are done in small steps according to the simulation model. Other possible not previous foreseen alterations are at the same time verified in the DES model to prevent any unforeseeable changes in the real-world system. Significant gains can be made by non-expensive measures and increased understanding for the related problems is important for successful improvements. Training of the personnel may be the key to increased overall efficiency for the company. The presented work shows the need of powerful tools such as DES combined with knowledge of disturbance reduction. This combination will enable results in increase of total output if it is applied.

Acknowledgements

The work presented in this article is funded by “PROPER”, a program by Swedish Foundation for Strategic Research and “IT Verkstadsprojekt”, a program funded by VINNOVA, Swedish Agency for Innovation Systems.

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