Simulation Assisted Models for Proactive Support in Intelligent Manufacturing Systems (SAMIN): An Industrial Case Study

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Abstract: This paper presents a novel architecture for offering a proactive decision support in the increasingly dynamic and flexible manufacturing environments. The managers need tools that may offer them intelligent support in the complex systems that ask for an effective and responsive management. We have developed SAMIN architecture and a supporting tool set (Simulation Assisted Models for proactive support in Intelligent Manufacturing Systems) to meet these needs. This architecture supports the concepts of phased developments in flexibility, integration and automation required by industry to develop towards CIM systems. The role of IT in this architecture is seen as an opportunity to improve the decision system and decision information synchronisation so that the inherent flexibility in the evolving CIM environments can be intelligently exploited. We believe such efforts will contribute towards IT supported intelligent Manufacturing Systems. The development of the toolset is focused on an industrial case study of a telephone manufacturing company, using real life data to build and evaluate various models. The results of the study indicate that, while a simulation based toolset provides a proactive knowledge generation environment for more effective decision making, it is important to minimize the decision delays involved in finding the desired solution. Towards this, the application of Artificial Neural Networks (to replace the simulator), Simulated Annealing (for optimization of desired parameters using simulator as well as ANN as a test bed) and Taguchi Methods (to optimize the simulation experimentation and to ensure focus on important factors), have been found to be very useful in enhancing the decision responsiveness.

Another important direction to improving the responsiveness of the manufacturing system, i.e. the effect of utilizing different levels of flexibility available within the manufacturing system on the overall makespan performance, has been studied, using a SAMIN based toolset. The results indicate that, with the utilization of increasing levels of flexibility, the overall makespan performance improvement tapers-off, while at the same time the shop floor control has to deal with higher levels of complexity, which may affect the responsiveness. Hence a judicious utilization of flexibility level may have to be evolved for a particular manufacturing situation, keeping in view the level of automation and the required responsiveness.

Professor **Subhash Wadhwa** (Eur. Ing., C. Eng.) received Ph.D from UCG, Ireland, while working on an ESPRIT project at CIMRU. He extensively contributed to the development of generalized simulators and expert systems for flexible assembly systems. Subsequently he worked for DEC (a US multinational), in Knowledge Engineering, and contributed to another ESPRIT project on Integrated Manufacturing Planning and Control Systems. He is currently Professor at Indian Institute of Technology, New Delhi. He has over 60 research publications including several reputed international journals, edited books and conferences. As chief consultant, he has successfully completed many industry projects apart from leading several Government sponsored Industrial R&D projects. He has originated novel research themes: decision and information delays involving Decision-Information Synchronization (DIS) applications in CIM, Supply Chains, e-Business; DRIS architecture for Agile Manufacturing; SAMIN architecture in IMS context, etc. These themes are motivated by his global Industrial experiences since 1988 and he actively promotes the judicious use of IT in SMEs, aiming to increase flexibility in a time-based competition. He has been a Consultant/Contributor/National-Expert to many International bodies EC, UNIDO, CW, APO (Tokyo), etc. *He is dedicated to the goal of bringing synergy between Academics, Industry and Research.*

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1. Background and Motivation

This paper enriches our overall research theme, which aims at intelligently exploiting the flexibility in CIM environments (e.g. FAS and FMS systems) by a judicious use of Information Technology. It is represented by works of Wadhwa, Maguire and Browne (1986) where the concept of *a decision point framework* was first proposed for exploitation of flexibility in discrete part manufacturing systems. Wadhwa, Felix and Browne (1987) used this framework to model flexible assembly systems in which the *decision points exercised control on flow of entities such as material, resources and information* through a flexible assembly system. Subsequently, Wadhwa and Browne (1988) also suggested a focus on *interaction delays* caused by processes involving the control on flow of these entities. With a focus on flexible systems, Wadhwa and Browne (1990) later proposed *three types of decision points* linking the decision (direction of status change) and information (system status) to exploit available flexibility in FMS in various forms. In our view the role of IT in CIM systems essentially involves the use of computers to integrate and automate the flow of decision and information as useful entities supporting the overall material flow processes, so that interaction delays are minimized. Based on this, Wadhwa and Agarwal (1993) suggested Flexibility, Integration and Automation as three key dimensions of CIM systems. Wadhwa, Caprihan and Kumar (1997) suggested a judicious use of Flexibility, Integration and Automation in flexible systems in the context of a review period status monitoring policy and introduced three forms of information delays. Wadhwa and Bhagwat (1998) proposed the concept of SCFM (Semi-Computerized Flexible Manufacturing Systems) with a focus on Decision-Information Synchronization (DIS) delays as a building block for phased CIM development. The judicious use of IT to reduce DIS delays in SCFM systems was discussed. Subsequently, in order to effectively and efficiently study the various interactions between Flexibility and DIS delays, Wadhwa and Bhagwat (1999) introduced the use of Taguchi Methods. Wadhwa and Aggarwal (2000) proposed focus on synergism between Flexibility, Integration and Automation (FIA) towards IT effectiveness in CIM systems. Wadhwa and Rao (2000) explored various forms of flexibility and indicated its evolving role as a meta-competence in the manufacturing systems. In dynamic manufacturing system environments, the flexibility offers both an opportunity as well as a challenge. The decision makers need to act both responsively and effectively to drive the flexible system towards continually improving time focused performance. This requires a proactive decision support that can intelligently offer potential improvement directions. The SAMIN architecture originated by Wadhwa (2000) is an attempt in this direction. The supporting tool set is developed and demonstrated in an increasingly flexible industrial environment as part of an Industrial R&D project led by the principal author.

The typical manufacturing system scenario involves multiple types of parts and multiple machines coupled with flexibility, the number of alternatives at the decision points becomes very large and decision making becomes very complex. Under such circumstances, a simulation based decision support system can help the shop floor manager evaluate a large combination of variables, in order to cover more of the feasible solution space, and so to identify more effective solutions. Simulation also provides proactive decision support and helps 'what if' analysis be carried out in a relatively detailed manner, on the model representing the logical behaviour of the real system and its current state. But currently, with the use of simulation-based techniques, the responsiveness of the shop floor manager will suffer, making the simulation tool unattractive for real life use. Especially, at the shop floor control level, the frequency of complex decision situations is relatively high and therefore responsiveness is as important as effectiveness. Often some sacrifice of the latter may be required to improve the former. The challenge is to identify a suitable course of action among several alternative solutions, in an effective and responsive manner so that the decision may be evaluated and implemented in a timely manner. If the available time permits, one would like to obtain and implement an optimal solution. However, this is not always possible. Sometimes the decisional responsiveness is more important than the solution effectiveness, due to the paucity of time. Thus there exists a need for developing *smart tools* that can offer more acceptable combinations of effectiveness and responsiveness to satisfy the decision-making needs of the shop floor managers. This motivated us in exploring the use of Artificial Neural Network (ANN), Simulated Annealing (SA) and Taguchi Methods, and developing an overall architecture supported by a simulation-based toolset for shop floor managers. The architecture offers alternatives to the end users, with the focus on 'effectiveness' if the quality of the results is the prime concern of the shop manager, whereas it is also 'responsiveness' driven when the time required to obtain a desired level of the expected results is the major concern.

Research Objectives

The SAMIN research is motivated by an aim to provide a general methodology for proactive decision support in Industry. The key objectives are:

a To explore the use of a domain specific, data driven simulator to gain greater user acceptance. Further integrate an experimental platform such as Taguchi Methods that involves fewer simulation experiments, to obtain a quick insight into factors that may need a priority focus.

b To explore the possibility of replacing the simulator by a trained ANN that can fulfil at least some management purposes much faster than a simulator. For instance highlighting which direction of change in the controllable variables is likely to be more useful.

c To demonstrate the efficacy of using novel algorithms such as Simulated Annealing (SA) that can automatically explore the simulated domain towards potential improvements. This will help the management obtain superior solutions in an automated manner. The expected limitation is total time and the processor usage.

d To explore the possibility of using the SA on the ANN that has been adequately trained by an existing domain specific simulator. This may alleviate the above limitations on the total time.

e To integrate the various tools so as to provide an overall proactive knowledge generation environment for the managers, to quickly identify the key factors, understand their interactions, and explore the impact of key controllable variables on the system performance, in terms of both effectiveness and responsiveness and their trade-off. This is an important aspect because sacrificing some effectiveness for the sake of improved responsiveness may be justified in the industrial context, at least for some managerial purposes. Keeping in view the fact that the managerial purposes and the available time for seeking various improvements may change quite often, it is expedient to provide relevant alternative options as an integral part of the architecture itself.

f Another major direction is to provide some insight to the shop floor managers on the effect of utilizing different levels of flexibility available within the manufacturing system for the overall makespan performance. This is particularly important as utilization of higher levels of flexibility entails higher levels of control complexity.

2. Literature Review

The use of simulation as a proactive knowledge generation tool has been well approached in the literature. Wadhwa and Browne (1988) have used simulation models to show the usefulness of decision points for exploiting flexibility in the FMS control context. According to Law and McComas (1990), simulation provides a ground for study of the design of new systems to evaluate and compare the performance of existing complex system in 'what if' analysis. Norman (1990) places simulation as a platform ideally suited to help organisations improve their manufacturing operations. According to Wong et al (1994) survey of industrial companies found simulation to be one of the most frequently used techniques. According to Hlupic and Paul (1996), simulation provides the flexibility of experimenting with a model of complex and dynamic manufacturing system by changing any parameter of the system.

However, reducing the time required for finding the desired result using simulation has been an important concern for many researchers. Towards this, number of works have been reported using expert system, Taguchi methods, simulated annealing and artificial neural networks in combination with simulation efforts.

Wadhwa, Felix and Browne (1987) presented a goal directed data driven simulator that demonstrates the possibility of developing an expert system with heuristic knowledge that may guide a simulator towards various system performance improvements. Benjamin et al (1995) described an approach to system design, using computer simulation experiments under the Taguchi method. Kim, Min and Yih (1998) discussed the Integration of inductive learning and neural networks for multi-objective scheduling. In the paper they proposed an integrated approach of learning and competitive neural network for developing multi-objective scheduling. Simulation and competitive neural networks are applied sequentially to extract a set of classified training data which are used to create a compact set of scheduling rules through inductive learning. They also did a simulation-based experiment, to evaluate the performance of the resulting scheduler. Wadhwa and Bhagwat (1999) demonstrated the possibility of applying Taguchi methods for complex and dynamic systems such as the SCFM systems to study factor level interactions.

The main emphasis of this work is put on the interactions between the flexibility levels and the system responsiveness in terms of the level of automation available within the system. Utilisation of greater level of flexibility requires higher level of automation to keep the information and decision delays low enough so that the system responsiveness is fast enough to realise the benefits of using flexibility. This motivated the authors' explicit study of the effect of utilising different levels of flexibility available in the system on the overall performance.

3. Brief Description of the Manufacturing System Modelled

The development of SAMIN architecture is focussed on a telephone manufacturing company. The company manufactures telephone units of different models and colours. Currently they are manufacturing five models in approximately ten colours that may increase in near future. Each model can have several feature variations. The manufacturing facility comprises two sections namely, Plastic Parts Section (PPS) and the Assembly Line Section (ALS). In the PPS, different plastic parts of different models are manufactured.

The plastic and electronic parts of the telephone kits are assembled together to form a complete telephone unit in the Assembly Line Section. The final assembly of all the products requires two sub-assemblies of the handset as well as the base unit. Both the assemblies consist of various activities that have different activity times. The task of the manager is to schedule the workforce and the raw material according to the target such that the resources are used effectively. The prototype simulators and the simulation based decision support systems for both of the application domains were demonstrated earlier to the industry. Discussions held by the project team with the shop personnel revealed that further enhancement is needed to improve the responsiveness of the system. The system should automatically guide the decision-makers towards improvements. Based on this, the SAMIN architecture has been evolved and an integrated tool set that meets the needs of the changing decisional contexts for the end users has been developed.

The manufactured system modelled is briefly described below using the GRAI (Doumeingts et al, 1995) macro reference model (Figure 1) quite explicitly. This model as shown in Figure 1 assumes that the structure of a manufacturing system comprises sub-systems such as the decision, information and physical systems.

Physical system: The physical system comprises machines, materials, operators and techniques divided into workcentres. This is the operational level and the operating system is based on the working procedure related to the use of the physical system. There are seven plastic moulding machines and four telephone models. Each model consists of several parts and when all the parts are assembled together, it forms the complete handset or the base unit. In all there are more than fifty moulds of all the models. These models may have ten different colours. There is a particular mould for a particular handset or the base unit of the telephone unit. The shop manager's job is to schedule the order in such a way that all such constraints as to minimise makespan, to maximise machine utilisation, etc. are satisfied and his requirement is also met.

Operating system: This represents a set of feasible procedures used as shop practice. Some examples are described. When one mould is already on the machine and some other mould needs not to be loaded on the same machine then put the other mould into the queue unless the machine gets free. If the machine is free then load any possible mould that can be loaded on that machine. If there is light to dark colour change then on the same mould change the colour. If a mould is loaded on a machine, then that mould cannot be loaded on any other machine, since there is only one mould of each colour. Also, the bigger moulds are given priority over the smaller moulds while loading on high capacity machines. Smaller parts that are common to all the models and colours are manufactured in large quantities once every 3 or 6 months. Usually lighter colour parts are manufactured before the darker colour parts.

Decision system: The decision system represents a hierarchical structure with each level determined by a horizon and a time interval during which a decision keeps valid. The decision system contains the hierarchy of the various decision centres. Each decision centre makes certain decisions based on the requirement and the objective and/or on the constraints.

Information system: The information system provides the decision system with relevant information and provides a link between the decision system and the operating system. This permeates through the entire structure. A whole range of information is required at various decision levels as per the GRAI macro reference model. Each level requires a different set of information. At the physical system level, details of all the models available are required. Complexity will increase as the number of models increases. At the next level of information system, such information as the availability of moulds of all the components of a particular model, is needed. If a new model is introduced then first of all the required mould should be there. Also at this level the order file is broken into component levels, e.g. if the coral model is needed to be manufactured then such information as what is the total number of components it consists of, and the material required, etc. is needed. At the next level of the information system, information about the number of machines in working condition, available on that particular day, is needed. Information about the master file of the machines, moulds and set up time, is also required. The GRAI method views that decisions start and terminate the events within production management system which, in turn, changes the information status. These events determine the performance and operating characteristics of the system. As a production management system is a dynamic system, the decision will only be appropriate for a given time horizon. The GRAI model motivates us to view the decision, information and physical systems and their associated activities and events explicitly while modelling a system.

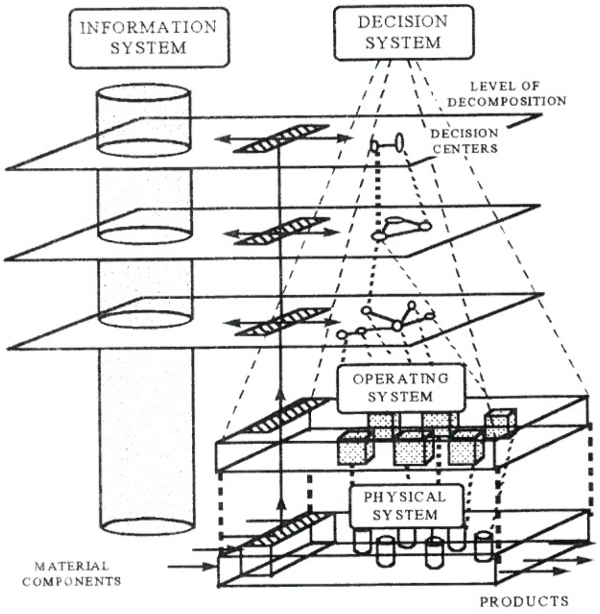


Figure 1.The GRAI Macro-reference Model

There is a need for enriching the periodic decision structure of the GRAI methodology with the discrete event based decision structure. The latter is facilitated by the Decision Information Synchronisation (DIS) framework proposed by Wadhwa and Bhagwat (1998). The SAMIN architecture supports the concept of domain specific management directed decision support which essentially combines the discrete event and the periodic event structures. Here the management offers the controllable parameters and the definition of decision points at which these can act. Such decision points can be periodic events during which the manager wishes to apply the decision choices.

SAMIN Architecture

Given the key requirements identified, we developed a tool set for an overall architecture called SAMIN (Simulation Assisted Models for Proactive support in INtelligent manufacturing systems). Figure 2 shows the SAMIN architecture as a methodology with a simulation-based tool set which provides proactive support to the shop managers. The conventional approach of using the simulator directly for performance analysis purposes is adequately enriched with a domain specific data driven experimental environment. Industrial experience acquired let us realize that the use of simulator without guidance could be too time consuming (i.e. poor responsiveness) for the end user who might have to carry out large number of 'what-if' experiments, to identify good decisions.

We need to supplement users' intuitive knowledge by using a module that allows a knowledge generation faster than a conventional simulator. The Taguchi methods based module is useful to help the design of experiments that may help the user to conveniently and quickly achieve the desired results using the simulator. For instance, the manager can know which factors require a priority focus and combination of what factor-levels is likely to be more useful. The knowledge gained from the Taguchi method of experiments can be transferred to generate intuitive experiments. So while designing the set of intuitive experiments, the user can use the knowledge of the Taguchi method. This would further enhance the responsiveness of the system. The next step is to use an artificial neural network to replace the simulator. The ANN, even if faster, may be less accurate (depending on the training of ANN), so it may help give good directional inputs in lesser time. The architecture allows that the user selects his preferred combination of tools depending on his needs for effectiveness and responsiveness. The left-hand portion reflects the user choice of using the simulator, while right- hand reflects the choice of using Trained ANN.

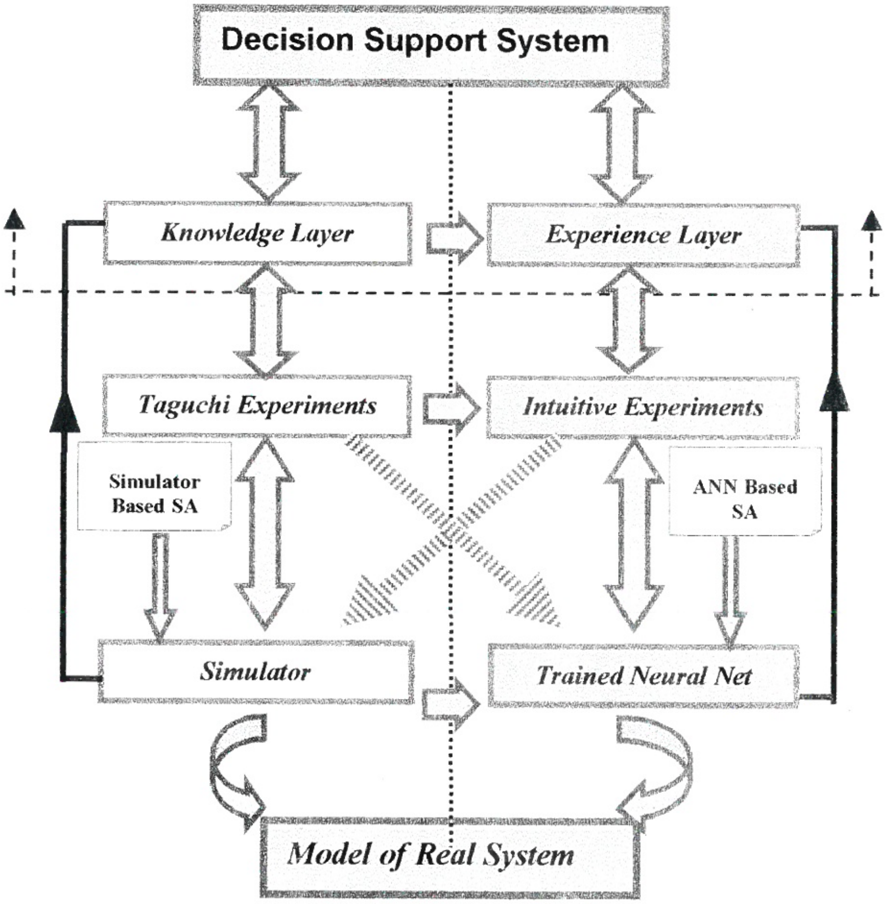


Figure 2. SAMIN Architecture

The next step is to build optimisation techniques such as the simulated annealing over the simulator/ANN. For seeking improvements in the system, the shop manager can go towards automated directional improvements of the controllable variables using Simulated Annealing (SA). The use of SA helps guide the simulator and/or ANN towards improvements. The shop manager either uses the simulator guided SA that would consume more time in finding the optimum solution or the ANN guided SA, where the same search may take less time. The dotted arrows show alternative combinations of user choices on the use of tools based on effectiveness and responsiveness needs. Thus the SAMIN architecture uses the tools ANN, SA and Taguchi Methods as the key components of the tool set, to provide a proactive support to the shop manager.

Top layer in the SAMIN architecture is the knowledge and experience layer. The knowledge layer signifies knowledge generated by use of the simulator. The experience layer signifies users practicing knowledge further enriched with knowledge layer as shown in the architecture. The dotted lines with arrows show the scope for future efforts, suggested by this architecture. The tool set for the SAMIN architecture is aimed at demonstrating the potential benefits, limitations and scope for future research. For demonstrative purposes a deterministic environment is modelled using an industrial case study based on the telephone manufacturing company. The features of the SAMIN tool set as implemented for the above industrial case study may be summarised as follows:

a The SAMIN tool set is aimed at assisting the shop floor manager in shop planning, scheduling and control of the Plastic Parts Sections and Assembly Line Sections of the telephone manufacturing facility.

b The tool set enables simulation of various manufacturing scenarios for different orders and from different initial states of the manufacturing facility. The simulation results include performance of the system in terms of makespan and average machine utilisation for eight types of sequencing decision logics at each machine.

c The Taguchi module helps design the simulation experiments using the Taguchi method that may offer more useful combination of controllable variables with fewer experiments. The user may check the interactions between various factors by using ANOVA and ANOM analyses.

d The output analyser module is aimed at helping multi-objective analysis.

e The SA module is developed with a view at assisting the managers to identify the appropriate lot sizes where the number of tardy jobs is not large. It also finds the appropriate changes in controllable variables, to obtain improved system performances.

f The trained ANN is aimed at exploring if it may replicate the system much faster. Thus it may offer the potential to improve the system responsiveness.

g The trained ANN may also work in the optimisation environment (SA). This may further improve the system responsiveness.

h The user may also opt for a hybrid approach where quick results are obtained thanks to the use of ANN. This gives direction for improvement. Subsequently, simulator is used along this preferred direction.

i The user has the choice to go for ANN based SA or simulator assisted SA, depending on the time available to him. The latter offers greater effectiveness.

j Thus we may benefit from ANN for speed, Taguchi Method for giving priority focus and direction and SA for optimisation of the controllable parameters.

k The integrated tool set in SAMIN is designed to allow the user selects his preferred combination of tools depending on his needs for effectiveness and responsiveness.

4. Case Studies

The following are the three case studies carried out to demonstrate the usefulness of the ANN, SA and Taguchi method. In all the cases, the controllable variables have been selected to be the five types of set up times involved in changing the moulds/colours of the parts to be manufactured in the plastic parts section, namely light to dark with no mould change (LtoDNoMChg), dark to light with no mould change (DtoLNoMChg), light to dark with mould change (LtoDMChg), dark to light with mould change (DtoLMChg) and no mould conditions (NoMld). The decision logic uses control rules such as Shortest Processing Time (SPT), Longest Processing Time (LPT), Earliest Due Date (EDD), Mould Setup Time (MST) EDD modified rules such as EDD_SPT_MST to signify first priority for EDD, then SPT followed by MST when ties are there, etc.

Case Study 1

To explore the possibility of using a trained ANN to replace the simulator.

In these case studies, simulation experiments have been carried out using a simulator as well as a trained ANN and the results have been compared to explore the possibility of replacing the simulator by a trained ANN.

The objectives of the simulation experiments are to study the effect of change in the setup times (- for decrease and + for increase) on the makespan performances of the system for different sequencing logics. The methodology involved by the case study are use of Taguchi OA data sets for simulation and training of ANN and random data sets for the testing of the ANN. First of all we design experiments through using the Taguchi method. Then we simulate all the experiments to get the results. We then use these data to train the ANN. To test the ANN, we generate some random data sets from Taguchi designed experiments as shown in Table 1. Then we compare the results obtained first by ANN and then by using the simulator. The combined results of the ANN and the simulator are shown in Table 2.

Table 1. Taguchi Designed OA

LtoDNoMChg	DtoLNoMChg	LtoDMChg	DtoLMChg	NoMld	Logic
-40	-50	40	0	0	(SPT)
-40	-50	-30	0	0	(SPT)
-40	-40	-30	0	0	(SPT)
-30	-40	40	0	0	(SPT)
-40	-50	-30	0	0	(LPT)
-40	-50	40	0	0	(LPT)
-40	-50	40	0	0	(LPT)
-30	-40	40	0	0	(LPT)
-40	-50	-30	0	0	(EDD)
-40	-50	40	0	0	(EDD)
-40	-40	-30	0	0	(EDD)
-30	-50	-30	0	0	(EDD)
-40	-50	40	0	0	(MST)
-30	-40	-30	0	0	(MST)
-40	-50	-30	0	0	(MST)
-40	-40	40	0	0	(MST)
-30	-40	-30	0	0	EDD_SPT_MST
-40	-40	40	0	0	EDD_SPT_MST
-40	-40	-30	0	0	EDD_SPT_MST
-40	-50	-30	0	0	EDD_SPT_MST
-30	-50	40	0	0	EDD_LPT_MST
-40	-50	-30	0	0	EDD_LPT_MST
-40	-40	40	0	0	EDD_LPT_MST
-40	-50	40	0	0	EDD_LPT_MST
-30	-50	40	0	0	EDD_MST_SPT
-40	-40	40	0	0	EDD_MST_SPT
-30	-40	-30	0	0	EDD_MST_SPT
-40	-40	40	0	0	EDD_MST_SPT

-30	-50	-30	0	0	EDD_MST_LPT
-30	-40	40	0	0	EDD_MST_LPT
-30	-50	40	0	0	EDD_MST_LPT
-40	-50	-30	0	0	EDD_MST_LPT

Table 2. Result of the Experiment by the ANN and the Simulator

	Controllable Variables (Setup times)					Measures of Performance		
LtoDNoMChg	DtoLNoMChg	LtoDMChg	DtoLMChg	NoMld	Logic	NMakeSpan	SMakeSpan	ErrorMS
-40	-50	40	0	0	1	572	584	2.05
-40	-50	-30	0	0	1	570	582	2.15
-40	-40	-30	0	0	1	568	582	2.49
-30	-40	40	0	0	1	568	566	0.31
-40	-50	-30	0	0	2	566	528	7.09
-40	-50	40	0	0	2	540	532	1.41
-40	-50	40	0	0	2	540	602	10.36
-30	-40	40	0	0	2	604	612	1.39
-40	-50	-30	0	0	3	604	612	1.39
-40	-50	40	0	0	3	604	610	1.05
-40	-40	-30	0	0	3	602	604	0.43
-30	-50	-30	0	0	3	608	602	0.9
-40	-50	40	0	0	4	532	544	2.28
-30	-40	-30	0	0	4	544	568	4.3
-40	-50	-30	0	0	4	546	576	5.24
-40	-40	40	0	0	4	588	576	2.05
-30	-40	-30	0	0	5	588	604	2.71
-40	-40	40	0	0	5	588	566	3.78
-40	-40	-30	0	0	5	566	566	0
-40	-50	-30	0	0	5	566	588	3.78
-30	-50	40	0	0	6	560	580	3.49
-40	-50	-30	0	0	6	560	580	3.49
-40	-40	40	0	0	6	560	570	1.91
-40	-50	40	0	0	6	588	566	3.81
-30	-50	40	0	0	7	576	578	0.42
-40	-40	40	0	0	7	596	580	2.72
-30	-40	-30	0	0	7	582	577	0.73
-40	-40	40	0	0	7	600	576	4.13
-30	-50	-30	0	0	8	524	566	7.46
-30	-40	40	0	0	8	504	510	1.33
-30	-50	40	0	0	8	524	526	0.42
-40	-50	-30	0	0	8	540	524	3.01

Figure 3 shows the comparison of the results of ANN and of the simulator. Ideally we would like to see that both lines coincide with each other, but since we set an error tolerance of 0.01% and limited ourselves to a smaller number of data sets for training purposes, there is normally a difference between the ANN and the simulation results. We can also see that the two lines in the graph follow the same pattern. This may help give directional guidance to the end user.

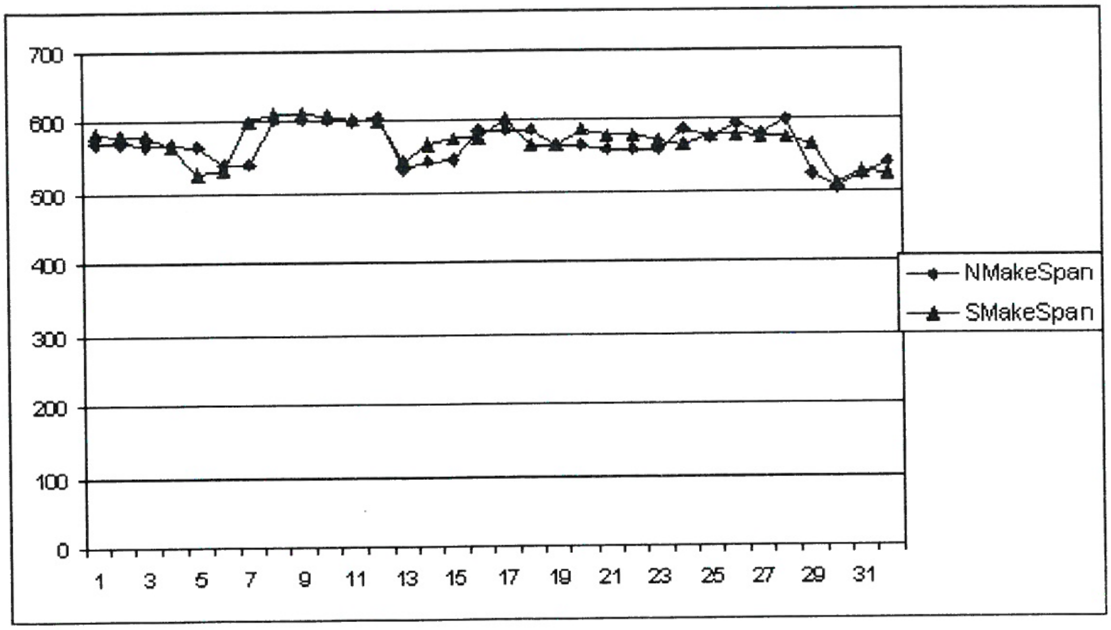


Figure 3. Comparison Graphs for ANN and the Simulation Results

We can observe that at some points the ANN is able to predict the simulation result. The average error is about 3%, which may be acceptable considering the time in which ANN calculates the results. So we can say that in this case ANN may replace the simulator. As stated earlier, if we are able to replace the simulator by an ANN then the responsiveness of the system will be higher (also keeping the effectiveness, i.e. average error, at acceptable limit).

Case Study 2

In this case study, we took another order file. The simulation result of this order file shows that there is less deviation between the values of different data sets. The ANN is trained using the Taguchi OA data sets and tested on random data sets. The testing result of ANN is shown in Table 3.

Table 3. ANN and the Simulation Result of the Random Data Sets

LtoDN MChg	DtoLNM Chg	LtoDMC hg	DToLM Chg	OnlyM Chg	Logic	NNMakeSp an	ActMakeS pan	ErrorMakeS pan
-7.06	-5.33	-5.8	-2.9	-3.02	SPT	640	629	1.76
-7.75	-0.14	-7.61	-8.14	-7.09	SPT	637	628	1.37
-0.45	-4.14	-8.63	-7.9	-3.74	SPT	639	621	2.9
-9.62	-8.71	-0.56	-9.5	-3.64	SPT	637	621	2.54
-5.25	-7.67	-0.54	-5.92	-4.69	LPT	640	629	1.68
-2.98	-6.23	-6.48	-2.64	-2.79	LPT	641	629	1.92
-8.3	-8.25	-5.89	-9.86	-9.11	LPT	636	628	1.22
-2.27	-6.95	-9.8	-2.44	-5.34	LPT	640	628	1.84
-1.06	-9.99	-6.76	-0.16	-5.75	EDD	641	629	1.92
-1	-1.03	-7.99	-2.84	-0.46	EDD	635	622	2.15
-2.96	-3.82	-3.01	-9.49	-9.8	EDD	638	629	1.45
-4.01	-2.78	-1.6	-1.63	-6.47	EDD	641	630	1.81
-4.1	-4.13	-7.13	-3.26	-6.33	MST	640	629	1.79
-2.08	-1.86	-5.83	-0.81	-4.58	MST	642	629	2.04
-9.06	-2.61	-7.85	-3.79	-2.9	MST	635	621	2.21
-9.19	-6.32	-6.28	-4.28	-0.98	MST	639	621	2.82
-5.61	-6.94	-9.14	-8.35	-0.23	EDD_SPT_MST	638	621	2.73
-5.43	-9.16	-4.3	-6.78	-5.02	EDD_SPT_MST	638	621	2.7
-5.14	-4.63	-3.53	-4.05	-2.7	EDD_SPT_MST	640	629	1.71
-0.56	-2.44	-9.79	-0.61	-3.9	EDD_SPT_MST	642	629	2.12
-3.65	-4.9	-1.56	-4.74	-2.57	EDD_LPT_MST	641	622	3.1
-6.29	-5.42	-1.56	-9.39	-6.54	EDD_LPT_MST	630	621	1.44
-5.06	-3.9	-1.07	-7.84	-4.6	EDD_LPT_MST	640	621	3
-7.54	-5.96	-8.33	-0.19	-2.1	EDD_LPT_MST	640	629	1.79
-0.74	-1.05	-3.32	-1.28	0	EDD_MST_SPT	643	630	2.13
-5.37	-6.57	-5.44	-8.27	-0.82	EDD_MST_SPT	639	621	2.85
-1.92	-6.79	-4.54	-3.57	-1.5	EDD_MST_SPT	641	629	1.89
-2.52	-5.51	-6.3	-8.24	-3.62	EDD_MST_SPT	640	635	0.72
-3.63	-4.52	-6.85	-9.68	-7.1	EDD_MST_LPT	628	630	0.36
-5.51	-7.56	-6.32	-7.12	-9.45	EDD_MST_LPT	635	631	0.61
-3.21	-6.12	-1.02	-3.25	-8.12	EDD_MST_LPT	640	635	0.72
-5.32	-1.31	-4.35	-5.36	-7.32	EDD_MST_LPT	645	643	0.31

In this case we can see that the ANN is able to predict the results quite close to the simulation results. The average error between the ANN and the simulator results is of approximately 2%. This indicates that when the difference among values of data sets is lesser, then the ANN may be trained successfully, even with a smaller number of data sets. The graphical representation of the result is shown in Figure 4.

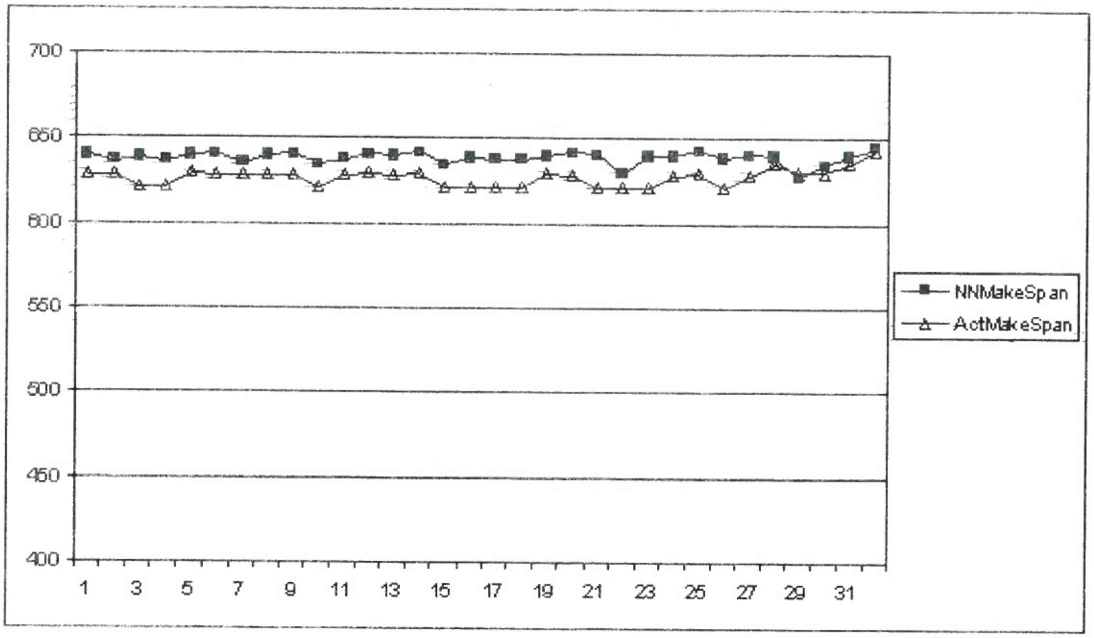


Figure 4. Comparison Graph of the ANN and the Actual Results

We may conclude from the above experiments that for some purposes the ANN is to offer a useful possibility to replace the simulator if it can be effectively trained. A trained ANN is far more responsive than the simulator to conduct what-if analysis, especially for comparison purposes. This may improve the decisional responsiveness of the managers dealing with complex decision situations. We performed several experiments in order to verify this utility. In most of the experiments we found that the ANN could replace the simulator provided the training was good. But to validate this interesting possibility for all the scenarios, further research is required in this direction.

The major drawback with the ANN is its training. Usually the training of the ANN depends, apart from other parameters, on the nature and the number of data sets. This also depends on the variations among values of the data sets. We have used different methods for the training and testing of ANN. We observed that with the help of Taguchi OA the number of data sets required for the training is smaller. In one of the sample cases we found that the ANN is trained with more than 95% accuracy. This gives indication that the Taguchi method may provide an efficient way of training an ANN. We also observed that the trained ANN may also be aimed at using for purposes of simply indicating the directional benefits. For instance, it may incur a prediction error that may not be acceptable to the user. But for some purposes where the user only needs guidance on whether an output will increase if an input is increased, the ANN may still be useful.

Case Study 3

To demonstrate the usefulness of a simulator based SA and ANN guided SA.

In this case study, experiments have been carried out to determine the level of set up time for maximum benefits. In SA module we specify the order file, the scheduling rule and the scheduling time. It changes the controllable variables, say the set up time randomly, and monitors the effect on performance measures. If there is an improvement in the performance measures then it continues its search until it gets the optimum solution. The module stops when it reaches to the desired tolerance limit specified by the user or runs up to a maximum of 100 cycles. This complete process takes approximately 40 minutes on a desktop computer and it determines the appropriate values for the various factors. The variation of makespan during SA iteration is shown in Figure 5.

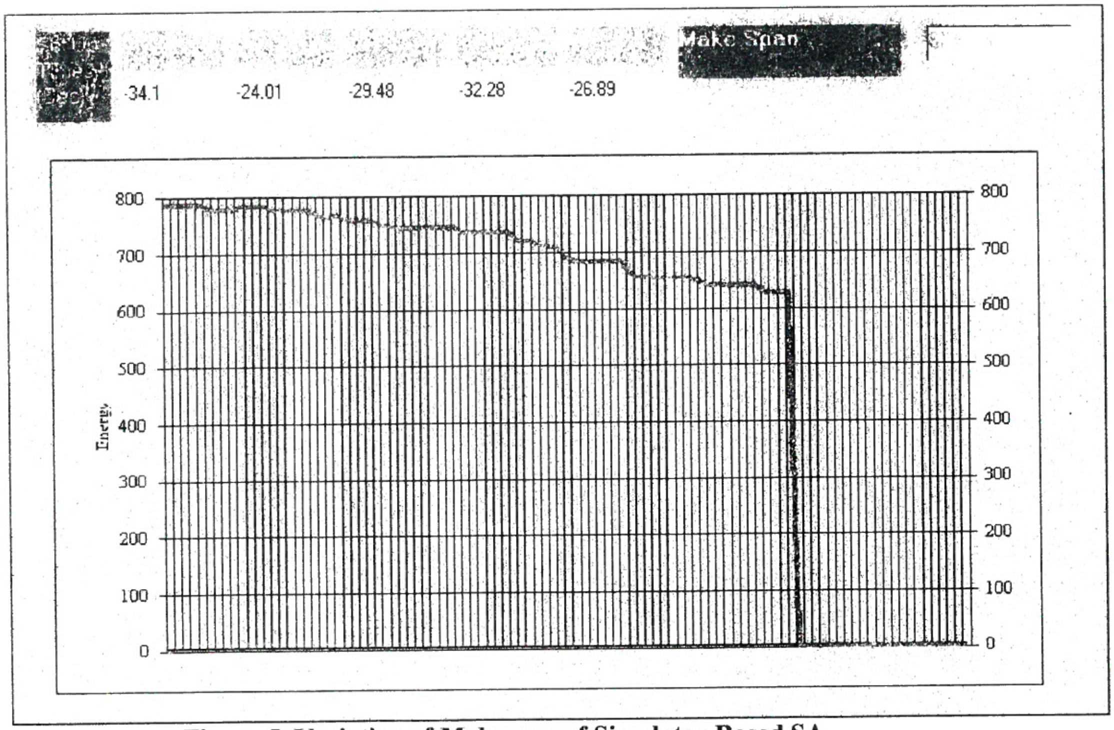
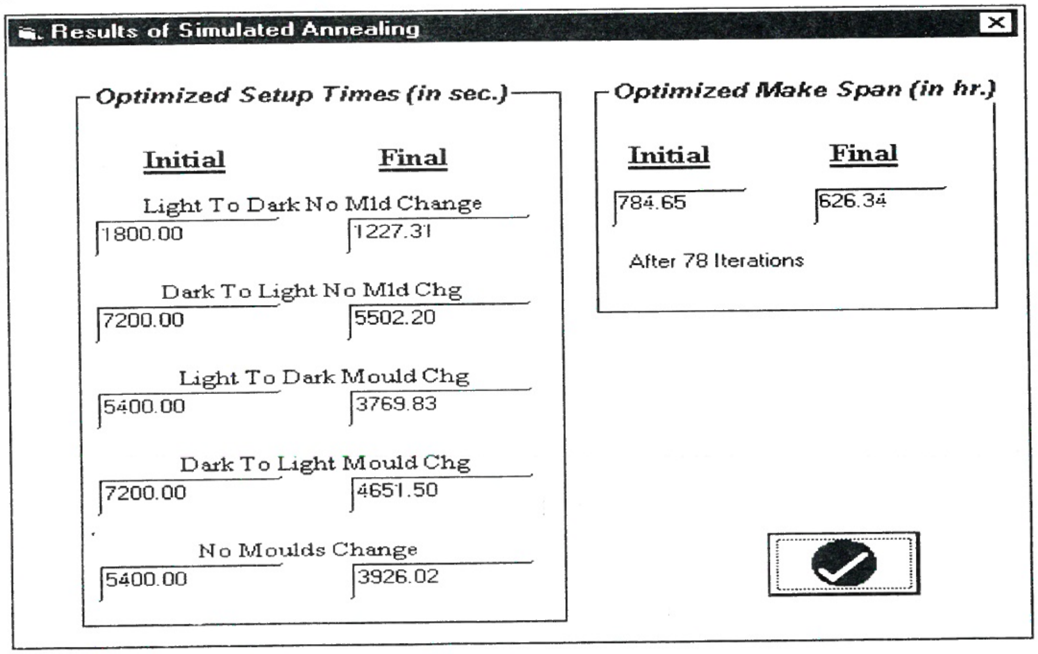


Figure 5. Variation of Makespan of Simulator Based SA

Figure 6 shows the summary of changes made for each type of set up times and corresponding changes made in the make span. This is done on the simulator based SA, which took a lot of time. Then we repeated the same procedure on the ANN guided SA, which is comparatively less time- consuming.



Results of Simulated Annealing

Optimized Setup Times (in sec.)

	Initial	**Final**
Light To Dark No Mld Change	1800.00	1227.31
Dark To Light No Mld Chg	7200.00	5502.20
Light To Dark Mould Chg	5400.00	3769.83
Dark To Light Mould Chg	7200.00	4651.50
No Moulds Change	5400.00	3926.02

Optimized Make Span (in hr.)

Initial	**Final**
784.65	626.34

After 78 Iterations

Figure 6. Result of the SA Module

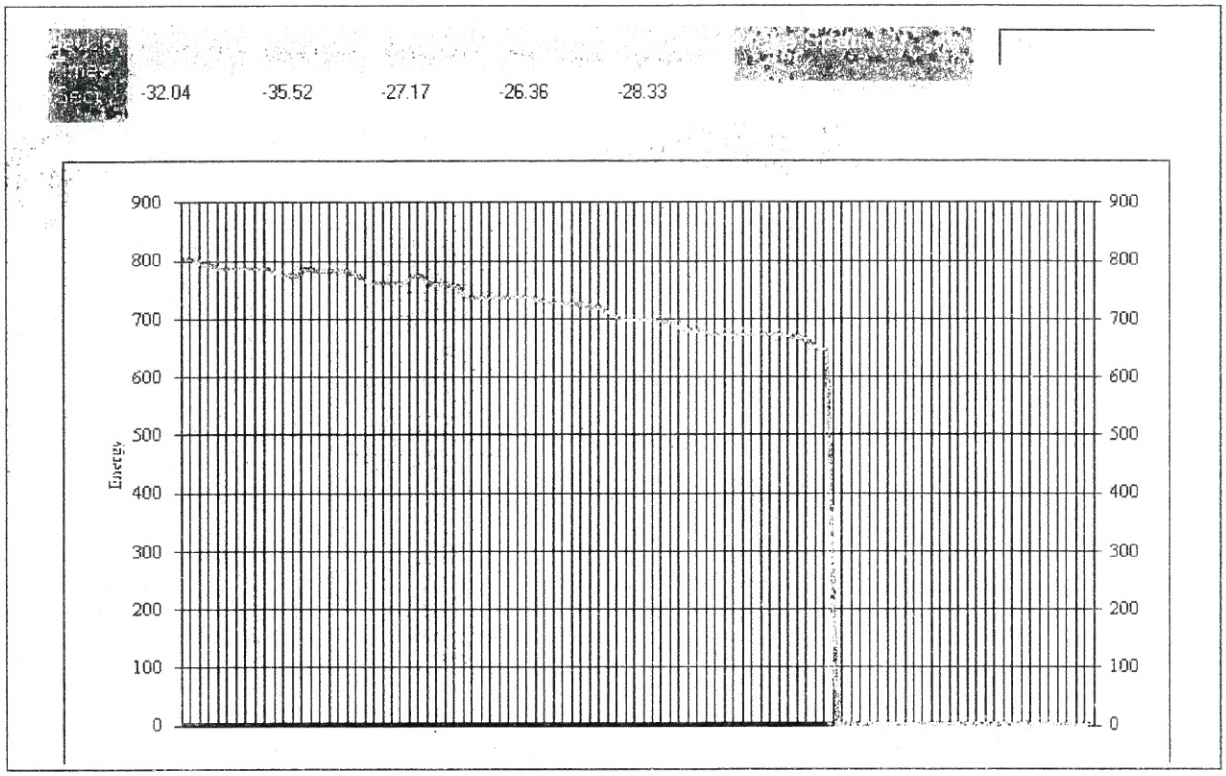
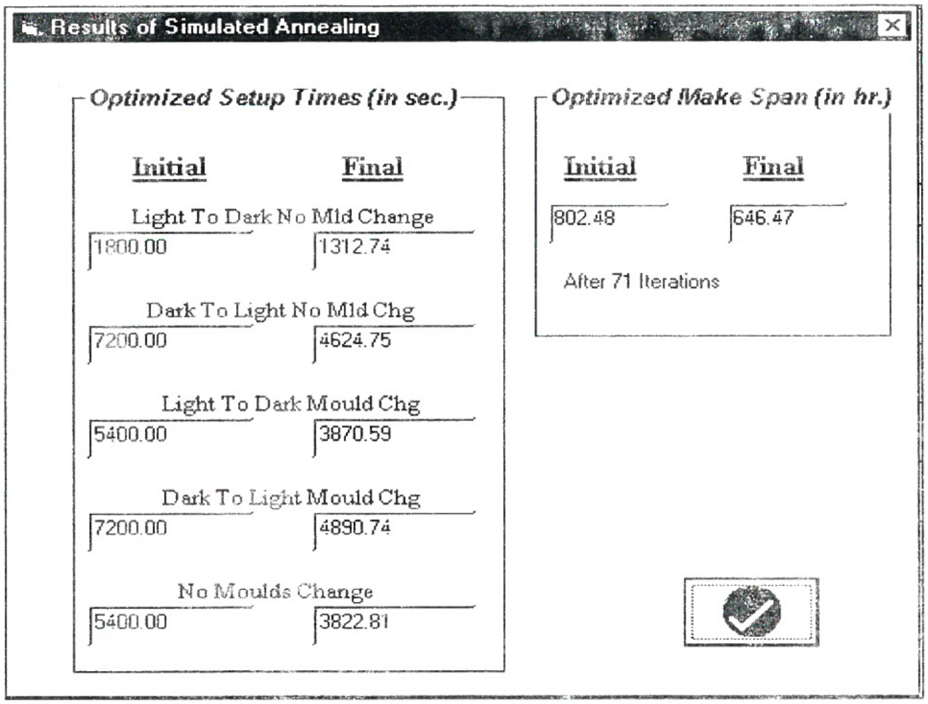


Figure 7. Variation of the make-span of ANN based SA

Figure 7 indicates the variation of makespan during an iteration of the ANN based SA. The Figure shows that the graph pattern of the ANN guided SA follows closely to that of the simulator based SA. Figure 8 shows the changes made in the initial values of these variables.

The above case study shows that ANN may successfully replace the simulator in an optimisation environment as well. The only limitation is the training of the ANN. In this case the ANN need to be trained with a larger number of data sets so that it may predict the output for any input variable. Time - saving is enormous if we use the ANN guided SA.



Results of Simulated Annealing

Optimized Setup Times (in sec.)

Initial	Final
Light To Dark No Mld Change	
1800.00	1312.74
Dark To Light No Mld Chg	
7200.00	4624.75
Light To Dark Mould Chg	
5400.00	3870.59
Dark To Light Mould Chg	
7200.00	4890.74
No Moulds Change	
5400.00	3822.81

Optimized Make Span (in hr.)

Initial	Final
802.48	646.47

After 71 Iterations

Figure 8. Result of ANN based SA

We can see that at the optimal point the value of the makespan using ANN guided SA is about 646 hours. The result of the above scenario using the simulator based SA comes out to be about 626 hours. Therefore there is a 20 hours difference between the two results. When we use ANN guided combinations and feed in the simulator, the actual result (make span) is about 630 hours. Thus we see that there is not so great a difference between the results of the ANN based SA and the simulator guided SA. This shows that there may be a possibility to replace the simulator by a trained ANN in the SA based optimisation environment.

Flexibility and Its Impact on the Effectiveness &Responsiveness of the Manufacturing System

Once established the importance of trade-offs between the effectiveness and responsiveness and a framework within which this is accomplished using the SAMIN toolset, we are motivated to study the role of flexibility of which impact on both the effectiveness and the responsiveness is a major one.

Understanding Flexibility

Flexibility is a subject of high debate in the current literature. Several attempts have been made to define, model, and measure the flexibility with a view at understanding its true nature and its effect on the performance of the manufacturing system. Some of the proposed definitions of flexibility include ability to change, ability to cope with uncertainty of change, as cited in Tincknell and Radcliffe (1996), ability of being usable for different production tasks, ability to reconfigure its resources so as to produce efficiently different products of acceptable quality, ability to respond effectively to changing circumstances, ability to respond cost effectively and rapidly to changing production needs and requirements, as cited in Benjaafar and Ramakrishnan (1996), an adaptive response to environmental uncertainty as cited in Gerwin (1993), a hedge against the diversity of the environment, as in de Groote (1994). Based on these definitions it can be summarised that the role of flexibility in a system is to enable the system to cope with change (certain or uncertain), in an effective and efficient manner. The change in the environment includes change in both the internal environment (resource bottlenecks, etc.) and the external environment (customer preferences, etc). Effective manner refers to the extent to which the effect of *change* has been successfully countered and efficiency refers to the time, cost and effort required to do this.

Several conceptual models have been put forward in the context of manufacturing flexibility, to understand how a manufacturing system uses its flexibility to counter the effect of changes in its environment. Xavier de Groote (1994) proposed a general framework for modelling and analysis of flexibility based on two elements: the set of technologies whose flexibility is to be compared, the set of environment in which these technologies might be operated. As per this model, flexibility is a property of technologies, and diversity (which represents the idea of variability, variety, complexity, etc.) is a property of the environment, and flexibility enables an organisation to counteract the effect of diversity in the environment. Tincknell and Radcliffe (1996) proposed a model for flexibility in terms of the underlying capability and versatility of the manufacturing system and its control systems, both human and mechanic. They define capability as the physical range of functions a system is capable of performing (such as the range of operations), versatility as the ability of the system to exist under different states (such as operating at different volumes, different mix, etc.). Versatility is realised through the application of automatic control to the inherent capability of the system, and flexibility is the application of system's capability and versatility to counteract the effect of uncertainty in the environment, through intelligent control. Here the important aspect is the application of intelligent control, because capability and versatility are necessary but not sufficient conditions for flexibility (for example a job shop offers versatility but this is rarely used due to lack of intelligent control). Gerwin (1993) went beyond the conventional understanding of flexibility (passive/defensive), and proposed that flexibility be employed on a 'proactive' (offensive) basis to redefine the competitive conditions, to create uncertainties in the environment which could not be counteracted by the competitors. Alternatively, flexibility can be 'banked' or held in reserve to meet the future needs. In this sense flexibility is an investment which enables a manufacturing system to compete in future. Wadhwa and Browne (1990) viewed flexibility as a means to provide choices at the operational level, to be exploited through various decision (or control) points. For instance if an operation on a product can be carried out on more than one machine (i.e. routing flexibility), then the decision point can opportunistically select the most desirable machine in the system.

Several attempts are also being made to characterise and to measure flexibility in its various forms. Benjaafar and Ramakrishnan (1996) described 19 types of flexibility and proposed a performance-based approach for quantifying the value of sequencing flexibility. In their approach, the relationship between flexibility and system performance was studied under a variety of design assumptions and operating conditions and these relationships were used to identify key characteristics of a measure of flexibility that is reflective of system performance. Chen and Chung (1996) discussed the relationship between various types of flexibility and proposed specific measures for machine flexibility and routing flexibility, which are fundamental to other types of flexibility. Das (1996) proposed five levels of measures (necessary, capability, actual, inflexibility, and optimality) for each type of flexibility, and proposed specific measures at these five levels for machine, routing, process, product, and volume flexibility. Piplani and Talavage (1995) discussed the entropic measure of routing flexibility. Kogut and Kulatilaka (1994) proposed a specific measure for operating flexibility for Global Manufacturing i.e. the flexibility of shifting production between various plants located in different countries. Gerwin (1993) discussed the ways of evaluating and changing a process flexibility, and measurement problems.

Judicious Use of Flexibility

When flexibility increases, the IT requirements also increase, with a resulting increase in the cost. As the level of flexibility increases, the cost of flexibility increases, [Starling, (Internet)], and at the same time the cost of not having flexibility decreases. The point where these two graphs intersect will give the ideal level of flexibility corresponding to the minimum cost. Recent work by Wadhwa and Bhagwat (1998) has indicated that IT effectiveness will play a vital role in realising the benefits of the flexibility. This work demonstrates that the benefits due to flexibility can be realised despite the presence of decision and information delays provided they are below a certain threshold level (by adequately investing in IT). This observation is very important in the Indian context, where most of the enterprises operate in semi-computerised environments characterized by phased IT investment. It implies that we need ensure a certain level of threshold IT investment before benefiting from the manufacturing flexibility.

Our current research on flexibility also indicates that flexibility can be used not only for effectively managing the product or process changes but also for improving the performance of the manufacturing system. For instance, Wadhwa and Bhagwat (1998) indicate that manufacturing flexibility in the form of routing and machine flexibility can be judiciously exploited towards lead time reduction in multi-product manufacturing systems. It is shown that this is achievable through a dynamic control of the flow of products and resources. The dynamic control requires IT enabled on-line control decisions supported by a desirable decision and an information system. However greater flexibility does not necessarily result in improved performance. A judicious level of IT enabled decision automation and information integration is required. Since flexibility and IT are both expensive, it is important to employ the right type and level of flexibility in a given environment.

Flexibility and System Responsiveness

Every manufacturing system provides a certain amount of inherent flexibility at different levels. Utilisation of these flexibility levels depends on the level of automation available in the manufacturing system and the control complexity acceptable for the management. This is closely related to the responsiveness of the system, as a higher level of control complexity with lower level of automation may result in poor responsiveness. Hence, when the system responsiveness is an important criterion, utilisation of flexibility beyond certain levels may prove to be counter -productive. Keeping these factors in view, the SAMIN toolset has provided for explicit study of the effect of utilisation of different levels of flexibilities, available in the manufacturing system, on the overall performance in terms of makespan and average machine utilisation.

Case Study of Flexibility in the Plastic Parts Shop

The plastic parts manufacturing system uses sixty-four types of moulds on seven types of machines. Each type of mould can be loaded on a certain number of machines depending on the size and on the technical feasibility. This gives raise to different levels of flexibility in using the mould-machine combinations. During this case study, these mould-machine combinations have been varied in four levels ranging from each mould capable of being loaded on only one machine (RFL0) up to several moulds capable of being loaded on four machines (RFL4). The effect of utilising these four levels of flexibility on the makespan performance is given in Figure 9, for different types of loading logic.

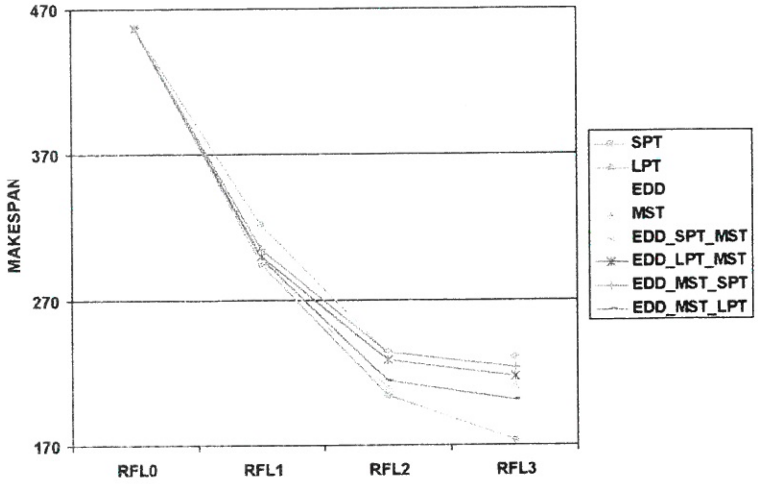


Figure 9. Role of Flexibility Levels on the Makespan Performance Under Unbalanced Conditions

The results indicate that, in this case, there will be an improvement in the makespan performance up to two levels of flexibility and that beyond there will be no benefit of increasing flexibility. The results also indicate that the sequencing logics are important at higher levels of flexibility. The case study has been repeated with a different order scenario involving much greater workload and with workload on all types of moulds closely balanced. The result is shown in Figure 10. In this case, the makespan improvement as observed for only one level of flexibility and beyond of which no improvement could be seen.

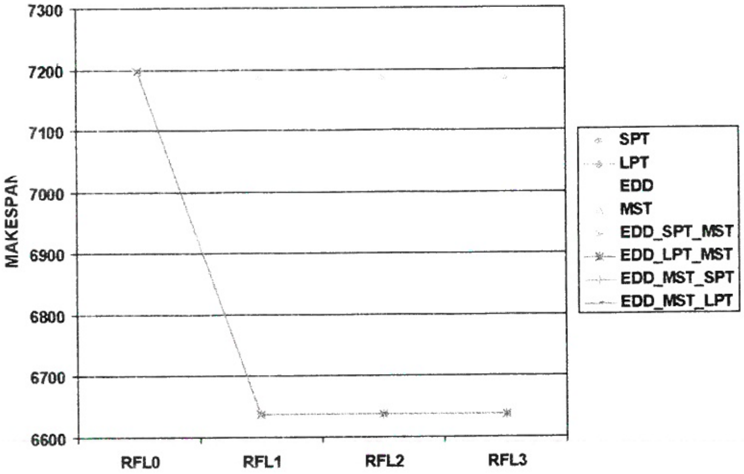


Figure 10. Role of Flexibility Levels on the Makespan Performance Under Balanced Conditions

From the above case studies we can see that it is important to evaluate the effect of utilizing the available flexibility in the manufacturing system for different manufacturing scenarios. Especially, when the system responsiveness in an important criterion, it may be useful to keep the control complexity low. In recognising this need, the SAMIN architecture enables quick evaluation of various possible options including the flexibility levels.

5. Conclusion

This paper presented our on-going research efforts on development of proactive support tools for managers in Industry. A novel architecture called SAMIN was presented along with its associated tool set developed and demonstrated in the industrial context. The key conclusions are:

a Simulation based tool set is a useful platform to provide proactive decision support for managers dealing with complex decision scenario.

b Taguchi methods when used in combination with simulation based toolset can greatly help to obtain a quick insight into factors that may need a priority focus.

c For a decision scenario where responsiveness is an important criterion, it may be useful to replace a simulator with a trained ANN. Here adequate training of ANN is important for accurate results and our studies indicate that Taguchi methods can be useful in generating the required training data set for ANN.

d Optimisation algorithms such as Simulated Annealing when used in combination with simulation based tool set help to obtain superior solutions in an automated manner. However, ANN guided SA will provide a good combination of effectiveness and responsiveness.

e Integration of various tools into a proactive knowledge environment will help the managers to quickly identify the key factors, understand their interactions and explore the most appropriate alternatives for their desired combination of effectiveness and responsiveness.

f It is important to evolve an appropriate level of flexibility for different manufacturing scenarios, to ensure the system responsiveness while, at the same time, to derive the benefits of flexibility.

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