Human performance modelling as an aid in the process of manufacturing system design: a pilot study

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1. Introduction

Once, ‘direct’ workers were considered to be a necessary evil, soon to be replaced by robotics and automation, but today the competitiveness of many manufacturing companies is still dependent on the flexibility and responsiveness that these people provide. This recognition has been demonstrated by the many newer management initiatives that emphasize developing the capabilities of the individual rather than attempting to remove them from the production system (Parker and Wall 1996).

It can be critical to the success of a manufacturing system design or redesign that human-centred factors are thoroughly considered. Traditionally, the design process has placed most emphasis on technological elements of the system, such as the number of machines, conveyor systems, buffer capacity and layout for part flow. At best, people-centred decisions have been addressed as a study of ergonomics. Unfortunately, such studies are mainly spatial considerations, and most often are carried out after most major investment decisions have been formed. At this stage, there is limited opportunity to redesign a system to take advantage of such factors as natural light, low noise levels, etc. A better approach would be to make a fuller consideration of the working environment at an earlier stage of manufacturing system design.

Manufacturing system modelling is generally recognized as a valuable aid to the strategic and tactical decision making in the design process. Such models are abstract representations of reality, and help to improve understanding and predictions about the performance of a manufacturing system. Typically, such models only treat people as a simple resource whose availability is time dependent (to represent shift patterns), who may work at a lower efficiency at times (to represent variances in worker motivation), and who follow simple and prioritized routines to represent management policies. If the capability of manufacturing system models to represent human behaviour could be extended, this would be a valuable means of gaining greater appreciation of human-centred factors much earlier in the system design process.

On this basis, this paper presents a pilot modelling methodology that enables the creation of quantitative models of the relationships between the working environment, the direct workers and their subsequent performance. This work has focused on proof of concept. A modelling methodology has been formed, it has been operationalized as a computer tool, and it has been evaluated in a trial at Ford Motor Company. However, to enable this research cycle to be achieved, the scope was restricted and the methodology contains a number of important approximations and assumptions. Nevertheless, having completed this important first step, an agenda can be proposed to steer the direction of future research.

This paper is structured to present first the need to model the performance of direct workers in manufacturing environments. To begin to address this need, a theoretical modelling framework is first developed, and then expanded to provide a detailed modelling methodology. There then follows a description of an industrial evaluation of this methodology at Ford Motor Company. The final section concludes this paper and identifies areas for future research.

2. Background: modelling within the process of manufacturing system design

The research presented in this paper has set out to improve modelling as an aid in the process of manufacturing system design. This section sets the context to this work. First, to clarify the focus of this research, a review of the literature describes how human performance is treated in conventional modelling tools. The second subsection highlights the wealth of current knowledge on human-centred factors, and this helps to illustrate the potential for expanding manufacturing system modelling capabilities.

2.1. Modelling within the process of manufacturing system design

The manufacturing system within many factories is a complex operation consisting of extensive interactions between people, information, materials and machines, for the purpose of producing a wide variety of products. Most manufacturing systems are complex, and so major design or redesign is a demanding task. Engineers and managers who are faced with this task can find guidance in recognised principles of good manufacturing system design (see Suresh and Kay 1998), they can learn from observations of successful organizations (see Womack et al. 1990), and they can tailor this knowledge to their own organizations using structured analysis and design methods (see Mills et al. 1996).

These design methods all have some form of evaluation, usually based on a combination of analysis, judgement and bargaining between the practitioners involved (Mintzberg et al. 1976). An analytical technique that is a valuable aid to manufacturing system design is Discrete Event Simulation modelling (DES) (Carrie 1988, Robinson 1994). Such a technique provides the basic constructs for quite a number of simulation tools currently being offered to industry, such as Witness (Robinson 1994). Such a tool enables the user to build a computer-based animation of the manufacturing system design being considered. This simulation is a coarse replication of the dynamic behaviour of the proposed system; it produces numerical performance indicators, and enables the practitioner to make informed judgements about the proposed system.

Simulation models are usually used to undertake a comparative analysis of system designs. Here, the practitioner, where possible, first builds a model of the existing manufacturing system (Law and Kelton 1991). This model is then tested and refined until it demonstrates acceptable validity. Alterations are then made to the model to replicate the proposed changes to the manufacturing system. Comparisons are made between the behaviour of these models, and these are taken as indications of how the performance of the real system will alter. The understanding and predictions they enable are a significant aid to the engineer and manager faced with a design problem.

DES-based tools tend to favour the modelling of the technological components of manufacturing systems, such as machines, conveyors and robotics. One reason for this, is that the behaviour of such elements is relatively straightforward to represent as a series of discrete events, and these representations are a reliable basis on which to predict behaviour. Hence, DES tools readily support the assessment of machine production rates, set-ups, and breakdowns on such measures as product lead-time and volume. However, as the elements of a manufacturing system become less deterministic in their behaviour, then they are more diffcult to model reliably.

This is especially a weakness when considering the human element in manufacturing system design and, in particular, the 'direct' worker. Within a factory, these people are dedicated to predominantly manual routines such as product assembly. There are many people oriented issues to be considered in manufacturing system design. From a physical perspective, factors such as noise, heat, illumination, etc, will affect the behaviour of the worker, so too do organizational factors such as work patterns, incentives and supervision. More subtly, behaviour is also in¯uenced by demography, attitudes, values, and beliefs of the workforce. All these peopleoriented issues have an effect, to a greater or lesser extent, on the performance of a manufacturing system.

Manufacturing system modelling tools, such as Witness, treat people as a simple resource that has limited availability. In a typical model, 'labour' is defined as a resource that is required by activities, such as 'machining' and 'assembly', to take place. Then, by varying the general availability and priorities of the labour resource, the model can be used to determine the required number of workers, shift patterns and routines. Currently, no DES simulation tools readily enable more detailed modelling of human performance. In this situation of uncertainty, the only contingency open to the engineer is to be conservative in expectations of production capacity, thus risk over-specifying a system and, as a consequence, cause sub-optimal capital investment. This gap is the target of the work described in this paper.

Other modelling techniques do exist to aid manufacturing system analysis. Baines et al. (1998) examine schematic representations (e.g. IDEF0), mathematical modelling (e.g. Queuing Theory), and other simulation techniques, such as System Dynamics (SD). Of these, SD is a powerful, if somewhat occasionally overlooked, technique for manufacturing system modelling (Baines and Harrison 1999). This technique can be a helpful aid to the practitioner seeking to dissect and represent complex relationships. However, to construct a model the practitioner still needs to have some semi-structured knowledge of the subject relationship. SD provides useful building blocks, but does not intrinsically provide any greater insight into human performance modelling than techniques such as DES. Finally, some specialist simulation aids do exist to consider human ergonomics, though these tend to concentrate on spatial analysis late in the design process.

2.2. The effect of the people factor and manufacturing system design

To appreciate the opportunity to extend the capabilities of modelling, it is useful to examine the impact that human-centred factors can have on manufacturing system performance. The following brief excursion into this literature illustrates both the potential human factors knowledge available to the manufacturing system designer, and the difficulty in assimilating such know-how in a way that is valuable to the practising engineer.

There is a wealth of social science literature that is relevant to manufacturing system design and performance. As early as 1935, Lewin (1935) suggested that the behaviour of a person is a function of their personal characteristics and the environment within which they exist. Since then, many studies have investigated the relationships between environmental conditions and the performance of direct workers. For example, considerable empirical work has focused on physical factors such as light, noise and temperature (Bonnes and Secchiaroli 1995). A broader view of the environment has been taken by researchers such as Furnham and Schaeffer (1984), who investigated the fit between a person and their somatic and psychological environment and the consequent stress levels.

The behaviour of the individual has itself been central to many studies. Singh and Srivastava (1981) established that morale is positively related to performance. Similarly, direct relationships with performance have been examined by authors such as Yitzhak and Ferris (1987), who found that task identity was related to job performance, and also Shapira and Griffith (1990), who investigated relationships between values and beliefs. More recently, Wall et al. (1990) examined the impact of operator control of machinery. They found that it related to higher job satisfaction levels and lower perceived levels of work pressure. Folkard (1996) describes how the alertness of an individual varies during a working day, Parker and Wall (1996) have explored the psychological perspectives of job design in modern manufacturing, and Furnham (1992) has investigated the relationship between personality and performance at work.

Like many disciplines, some areas have received greater attention than others. For example, experimentation and data collection methods have been a special area of interest since the seminal works of Roethlisberger and Dickson (1947). Similarly, considerable work has been carried out by researchers such as Tranfield et al. (1999), relating initiatives in human resource management to the performance of the firm. They focus on such topics as task orientated routines, team working and empowerment. Practice illustrates the value of such work, where the better manufacturing companies, such as Toyota, will build this continual improvement process into their culture.

When considering the social science literature, there are however two barriers that must be overcome for this work to be exploited at the stage of manufacturing system design. First, the work needs to be brought into the context of the company hosting the design activity; engineers and managers want to know the impact of 'their' practices on the likely performance of 'their' organization. Second, the practitioner has to sift through this information and the prescriptions to identify the relevant knowledge. Both of these barriers call for a method of bringing together the relevant social science knowledge, and representing this in a form that complements the manufacturing system design activity.

3. Research aim and method

Our research has set out to develop a human performance modelling capability that can be incorporated into DES modelling tools. The work described in this paper has been the first step in this process. Here, our aim has been to explore the human-performance modelling concept, to demonstrate the potential value, and to understand better the challenges facing research. There are therefore, three objectives addressed here, namely to:

(1) Form a theoretical modelling framework.

(2) Develop a prototype computer modelling tool.

(3) Evaluation of computer modelling tool and hence theoretical methodology.

Each objective has been addressed in a different way. The theoretical modelling framework has been based on a survey of the literature, along with conversations with academics and practitioners. This framework has been operationalized into a modelling methodology and then automated into a computer-based tool. At this stage, a set of assumptions and simplifications were made to enable this pilot work. For example, a decision was taken to restrict this initial research to focus on the impact of the physical environment. Finally, industrial-based assessment has considered whether the modelling methodology is valuable in practice. The remaining sections of this paper describe the realization of each of these objectives.

4. A theoretical modelling framework

The purpose of the theoretical framework is to guide the creation of the modelling methodology. Some frameworks are well established in the literature, with a seminal contribution made by Lewin (1935). He developed the expression:

$$B = f(P \times E), \qquad (1)$$

Where

B are the modes of behaviour,

P is the personality trait or whole personality,

E is the somatic and psychological environment of the individual.

Although the work of Lewin is dated, the basic expression remains unchallenged; rather more recent researchers such as Hackman and Oldham (1980) and Campion et al. (1993), have extended and refined this expression. It is useful to explore the form that a Lewin-based view of Human Performance Modelling (HPM) could take within the manufacturing system design process. Figure 1 illustrates how such modelling could be combined with DES to give a holistic view of manufacturing system performance. Here, the HPM is shown as passing information about worker reliability and productivity to a DES model (section 2.2), and to do this it would take as an input the person and environment data identified by Lewin. The reliability and productivity data relates to the symbol 'B' in the Lewin expression given above. Hence, the input into the HPM needs to be information that describes the people and their environment, which relates to the symbols 'P' and 'E' in the Lewin expression. Finally, the model itself needs to capture the relationship between input and output, relating to 'f ' in the Lewin expression.

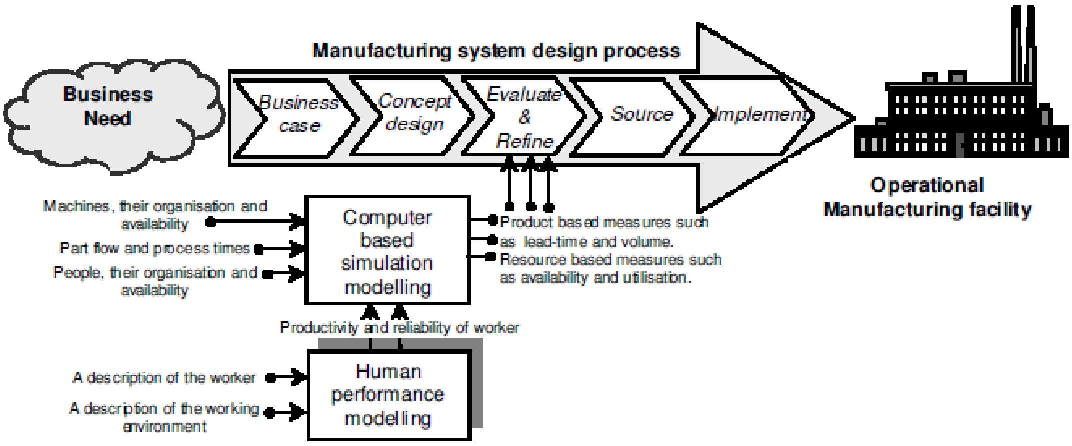

Figure 1. Human performance modelling as an aid in the manufacturing system design process.

5. Developing the modelling methodology

The modelling methodology is the operationalization of the theoretical framework. This section describes the set of rules and principles that have been developed to achieve this operationalization.

5.1. Scope and assumptions of the methodology

In this exploratory research, the methodology has been kept as simple as possible, and to do this a variety of assumptions and approximations have been made. First, as mentioned in section 3, the focus at this time has been on the physical working conditions internal to a factory, rather than the broader organizational environment of the worker. Second, workers have been treated as isolated individuals and, as such, the social interactions or behavioural tendencies of a group or team have not been addressed. Third, the secondary and longer-term effects of an environmental change are not considered. Fourth, the focus has been the behaviour and performance of people when directly carrying out production activities. Finally, the intention has been to express the effect of relationships between people and their environment, rather than to explore the form of such relationships in detail. These are all significant simplifications, and so Section 6 highlights the importance of addressing these issues in future research.

5.2. Establishing detailed indicators of worker performance

Section 4 suggests that the outputs from a HPM should be indicators of worker productivity and reliability, as illustrated on figure 1. Here we explore the method of providing this output in a form suitable for integration with a model created by a typical DES-based tool.

Behaviour is a description of the actions and routines of a person, whereas performance is the measurement of behaviour against selected criteria. On this basis, productivity and reliability measures are only meaningful as an output from a Human Performance Model (HPM) if they are related to specific actions of a person. For example, a particular worker may be more productive on assembly tasks than inspection tasks. Our approach therefore, has been to propose that predictions are given for worker performance against predefined 'core' production tasks. When constructing a model the core tasks are defined, such as 'pick and place', 'component alignment and fitting', or 'inspection', and then performance measures are provided relative to these core tasks. This is similar to the Task Assessment procedure offered by Buck and Greatorex (1996), as illustrated in figure 2.

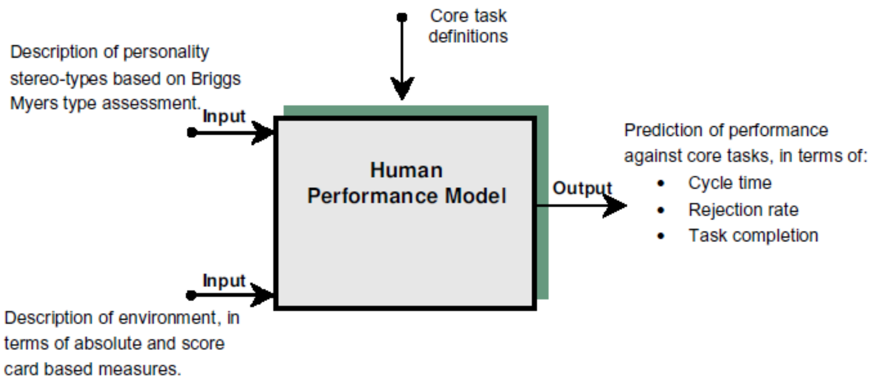

Figure 2. The basic modelling framework.

As for performance measurement, measures of productivity and reliability need to be defined in such a way that they are unambiguous when related to production tasks. Our approach therefore, has been to define productivity in terms of the relative time to carry out a core task. Hence, if the planned cycle-time for a core task is 15 minutes, if a productivity value of 100% was returned from the HPM, this would mean that the planned time would be achieved. However, if the productivity factor returned from the HPM decreased, then the time to carry out the task would increase, and vice versa.

A similar approach can be adopted for reliability, although reliability can be considered in two ways. First, reliability can be relative to the probability of a task being completed. Here, the term 'task completion' can be used to represent reliability. Secondly, reliability can be relative to the probability of a good output occurring from the task, such as a component being correctly positioned on a subassembly, and here, to avoid confusion, the term 'reject rate' can be used.

5.3. Capturing the conditions of a working environment

Section 4 suggests that one set of inputs to a HPM should be a description of the working environment, as illustrated in figure 1. Here, we explore a method of providing a quantitative description of the physical working environment.

Many aspects of the physical-working environment within the factory can be easily measured in absolute terms, such as noise, temperature, humidity, pressure and light. However, other factors, such as colours, cleanliness and working space around machines, are more diffcult to measure. One method is to assess these using a scorecard style measurement tool based on the Likert (1933) scale. This approach provides a relative assessment, for example machining area A is kept cleaner than B, and to do this the extremes on the Likert scale need to be well defined. However, by combining these two methods it is possible to generate a numerical description of the physical-working environment within a factory, as illustrated in figure 2.

5.4. Capturing the personal characteristics of people

Section 4 suggests that a second set of inputs to a HPM should be a description of the people working within the manufacturing environment carrying out core production tasks, as illustrated in figure 1. Here we explore a method of providing a quantitative description of these people.

When Lewin (1935) developed his expression of behaviour (equation (1) above), the symbol ‘P’ was given to represent the individual; more specifically, it signified the personality trait or whole personality of the individual. Since then, a wide variety of assessment procedures have been developed by psychologists to categorize people types. One of the most credible of these is provided by Myers and Briggs (1980), who provide a categorization of personality into 16 psychological types. Such assessment is susceptible to being faked, although some distortion can be avoided by clever questioning processes (Furnham, 1992).

Our approach has been to use a Myers-Briggs style assessment to capture the personality profiles of direct workers and then to cluster workers into personality stereotypes, as illustrated in figure 2.

5.5. Constructing a modelling tool

The final task is to establish a suitable computerized method of expressing the potentially complex numerical relationships that may exist between the inputs and outputs (how to represent ‘B’ shown in figure 1). A variety of modelling techniques were considered for this task, such as System Dynamics and Mathematical modelling, and from these it was decided to use an Artificial Neural Network (ANN). From a general point of view, an ANN is ideally suited for problems that are not well structured, and provide a capability to deal with imprecise data. A model is constructed by configuring the basic structure of the network, and then teaching the network the relationship that exists between input and output.

A prototype computer tool was then created to using Visual Basic software. Visual Basic was chosen due to its flexibility, ease of the implementation of mathematical functions, and feasibility of linking with databases and other software. This tool combined the modelling methodology with an ANN framework.

5.6. The computer based modelling methodology

On completion, this work has assimilated a set of rules and principles of a Human Performance Model (HPM), and formed these into a modelling tool that incorporates an Artificial Neural Network (ANN). Using this tool, five steps are necessary to construct a model of an existing manufacturing facility, these are:

Step 1. Define core tasks and performance indicators, and collect data about current state. Describe the behaviour of the workers in the facility in terms of core production tasks. For each routine, establish the relevant performance indicators and measure the steady state values. For example, ‘assembly’ might be the core task, the performance indicator might be ‘cycle-time’ and the steady state value might be 15 minutes.

Step 2. Define environmental experimental variables and collect data about current state. These are the aspects of the physical working environment within the facility that are to be modelled, for example temperature, light, noise, etc. For these variables it is necessary to establish values corresponding to a steady state performance of the system.

Step 3. Establish personality profiles of the production people. Using the personality assessment (section 5.4), determine the profile of each production worker. These can then be grouped into stereotypes.

Step 4. Collect relationship data, train and validate the modelling tool. Observe similar core tasks carried out, either by different types of people, or for different working environments. One method here is to observe how performance values for a specific task vary, as people and the environment change over a working day or series of days. Training and validation of the ANN can then take place.

Step 5. Experimentation with model. Once validated, a user should be able to vary the value of the experimental values and observe the effect in terms of the performance indicators. Within the scope of the model, this should show how the design of the working environment can affect the performance of direct workers.

6. Evaluation of the methodology

The modelling methodology is a concept; it is simply an approach to building models that capture the relationship between people, their environment and behaviour. The purpose of such models is to improve the decision making within manufacturing companies about the design of the working environment. This section describes the final step of our pilot work, which has been to test whether the proposed methodology can indeed fulfil the intended purpose.

6.1. Objective and scope of evaluation

The aim of this exploratory research has been to assess the validity of the modelling methodology (section 3). Therefore, the objective of this evaluation has been to establish whether the methodology ‘can work’, rather than critique 'how well' it works in a variety of applications. If the approach is valid, then future work can build from this and explore the limitations of the approach, whereas a failure to produce a single working model suggests that the whole modelling methodology is invalid. On this basis, evaluation has been based on a single and relatively straightforward experiment.

A suitable test-bed for experimentation was identified to be automotive assembly. Such an environment is worker intensive and tasks are often repetitious. A UK assembly plant at Ford Motor Company was visited, and one engine assembly department was chosen as a suitable modelling case.

6.2. Evaluation procedure

The chosen experiment was to work with a small group of Ford engineers to model part of an assembly line, which consists of 20 direct workers involved with various stages of engine assembly. The engineers were chosen because they held expert knowledge about the people and the department being modelled. The purpose of the modelling was explained to the group, and then they were asked to suggest a number of tests for the tool. A model was constructed and validated by the research team, and a series of proposed changes to the environmental conditions were then input. For each change, the Ford engineers were asked to assess the credibility of the results given by the model.

Three sets of criteria were used to assess the modelling methodology against the objective of this study. These performance criteria were adopted from the work of Platts (1993), and were:

Feasibility: Can the modelling methodology be applied?

Usability: Is the modelling methodology easy to apply?

Utility: Did the modelling methodology provide a useful output?

Using these performance criteria a set of associated indicators were identified, such as 'How long did it take to configure the model?' These formed the evaluation procedure for the methodology.

6.3. Data collection and Model configuration

Data collection, analysis, and model building were all carried out by the research team. In a typical engine assembly line, many workstations exist where a wide variety of components are assembled onto an engine by direct workers. Following our methodology, the first step in model building was to establish a set of core tasks that represent the activities at these workstations. The researchers carried out such rationalization and found seven different core tasks for engine assembly in this instance, namely: pick and place, fastening, adjusting, stock handling, release job, quality assurance and inspection. To complement the core tasks, three basic performance indicators were then identified, and these were; cycle time, rejection rate, and parts waiting for labour.

The second step in model building was to establish the personality profiles of the 20 workers in the department being considered. Interviews and analysis carried out by the research team revealed that there were, in this instance, four predominant different stereotypes. These were four of the five stereotypes termed:

The introvert and action orientated person (20% of workers)

The introvert and thinking person (10% of workers)

The extrovert and action orientated person (30% of workers)

The extrovert and thinking orientated person (35% of workers)

Other stereotypes (5%)

The third step in model building was to identify the environmental conditions around which to configure the model. Sixteen environmental states were chosen and these included; noise level, ventilation, temperature, daylight and cleanliness. This selection was based on discussions with the Ford engineers as to which conditions they would typically like to experiment with.

The final step in model building was to capture data that described the relationship between environment, personality and behaviour. This time, the interviewees were assembly workers at Ford and other assembly plants in the UK. Ten manufacturing plants were visited, and this provided data from 125 assembly workers. These data were then used to populate the ANN model. An overview of the subsequent model is given in figure 3.

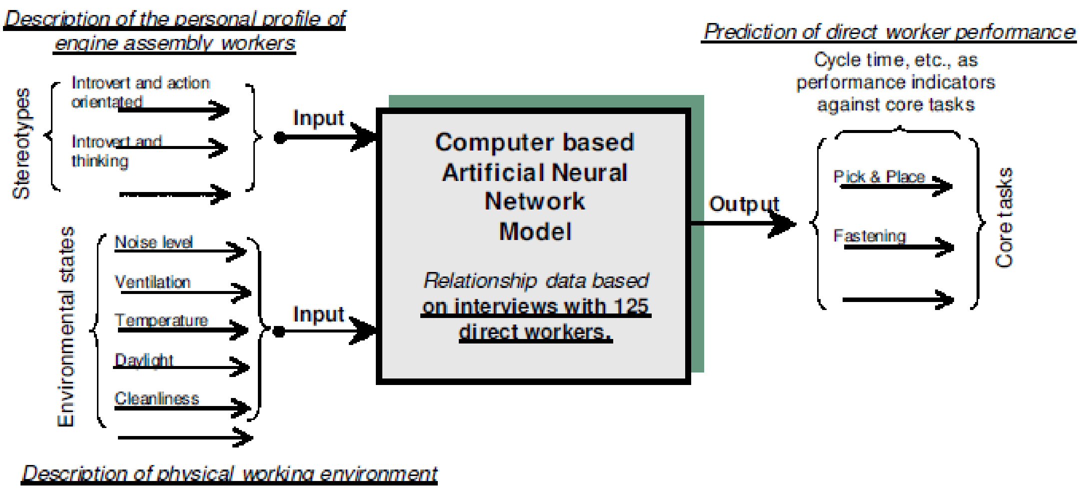

Figure 3. The structure of the pilot model.

6.4. Results

Evaluation of the modelling methodology was based on assessing feasibility, usability and utility. The following conclusions were drawn against each of these criteria:

Feasibility: Can the modelling methodology be applied? Both the Ford engineers and the researchers found that they could apply each step in the methodology in a straightforward manner.

Usability: Was the modelling methodology easy to apply? Significantly, both the Ford engineers and researchers found that the methodology was easy to apply. The most difficult stage was data collection about the personality profiles of the workers. More positively, the group was pleased with how the methodology reflected the needs of the engineer in the situation of manufacturing system design.

Utility: Did the modelling methodology provide a useful output? The model had limited validity. On the very first attempt, an environmental condition was chosen for which a wildly invalid response occurred. On investigation, it was apparent that this occurred because the ANN had insufficient data on which to form a valid response. However, once the questions from the engineers corresponded to the available data, then valid responses were given by the ANN. Where credible data existed, the model gave credible predictions.

On completion of the evaluation trial, the responses of the Ford engineers supported the credibility of the model. This was purposely an unambitious trial; however, it can be concluded that it has demonstrated that the modelling methodology has signifi- cant potential.

7. Conclusions

This has been an exploratory study. The paper has presented a pilot modelling methodology that is intended to provide a generic approach to modelling the relationship between direct workers, their environment and their subsequent performance. Although promising as a pilot study, this methodology has many simplifications and assumptions. The strongest component of the work was understanding the need of the practitioner, and establishing a pragmatic method of expressing the modelling challenge. On this basis, we have confidence that a Human Performance Modelling (HPM) capability would be a valuable addition to simulation tools, and that such a tool would, in abstract form, match that proposed in figure 1. Furthermore, this exploratory study has itself exposed a series of issues for future research, as discussed below.

First, the whole approach needs to be tested in more depth, and to focus on accuracy as well as credibility as a measure of success. This is a major undertaking requiring considerable commitment from and industrial sponsor, but is an essential step to test the form of the theoretical framework.

Second, methods of data collection about relationships need to be refined. In this study such data were gathered through intensive questioning of workers using semi-structured interviews and questionnaires by the research team. This approach can itself stimulate a change in production performance, this phenomena being commonly termed the

Hawthorne effect (Roethlisberger and Dickson 1947). The data collection instruments need to be refined to limit this susceptibility.

Third, HPM should better describe the individual. In this work a method was adopted of profiling the personality of an individual. However, there is little to suggest that personality is the appropriate measure to capture fully the traits that are the main indicators of how a person will react to a change in environment.

Fourth, HPM should account for the effects of social interactions on behaviour. A major simplification in the formation of the methodology was to treat people as isolated individuals. A group of people could be modelled, but no account was taken of the subsequent social interactions between individuals within the group.

Fifth, HPM should account for secondary effects of environmental conditions on behaviour. A second major simplification was to consider environmental effects as having a constant, permanent and singular impact on the behaviour of a worker. Future work should consider that dynamic relationships may exist between environmental change and behaviour, and that there may be a series of secondary effects of an environmental change.

Sixth, methods of validating the Artificial Neural Network need to be refined. The ANN is trained by correcting its response. There is not, however, a set point when the ANN can be considered to be complete, rather the validity of the network slowly improves as less and less corrections are necessary. The modelling methodology should include a procedure for assessing validity.

Seventh, a method is needed of ensuring that models are interpreted correctly. An increasing number of studies have highlighted the dangers associated with artificially bounding a change event in order to monitor that change (Fortune and Peters 1990, Stacey 1996) rather than positioning the event within the wider environment and over different time scales. As argued by Lemon (1999), even where phenomena cannot be included in the model, it is essential that they are incorporated into its interpretation. A limitation of the pilot methodology was therefore that it gave no guidance to the engineer or manager on how to interpret the results of a model, and hence its value in making an informed judgement.

Finally, this exploratory study has made an important first step in this area, having gone someway to establishing a generic methodology and illustrating the potential value. Our future work will now build from this foundation with a research agenda that will set out to address the issues mentioned above. The research design will also include a more careful consideration of the human-centred factors that are most likely to impact on the performance of a manufacturing system. This will enable a more careful consideration of the theoretical framework at the root of the HPM methodology.

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