Integrating Human Aspects into the Digital Factory

New Tools for the Human-oriented Design of Production Systems

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Abstract: Currently, comprehensive tools are being developed which shall improve the process of factory planning. These tools are referred to as the "Digital Factory" and comprise diverse features, from capacity planning of production resources to visualisation and simulation of a virtual workshop. In a micro-ergonomic view, human-centred functionalities and ergonomic workplace design and assessment can also be included. From a macro-ergonomic point of view, however, the integration of personnel-oriented simulation is still missing. This paper describes the main functionalities of these features and hints at first pilot software for their integration into the Digital Factory.

Key words: Digital factory, Ergonomic workplace design, Personnel-oriented simulation

1. THE DIGITAL FACTORY: A COMPREHENSIVE TOOL FOR FACTORY PLANNING

1.1 Graphic Simulation of Future Production Systems

Currently, computer-aided tools are developed under the name "Digital Factory" and are intended to help improve and accelerate the planning of new production systems. Meant as a set of comprehensive tools for designing, visualising and even running of future production systems in a computer model, the Digital Factory promises to reliably prognosticate dimensions and performance of the future production system long before its realisation. For this purpose, graphic 3D-modelling and visualisation tools are combined with functionalities of event-driven simulation and evaluation tools.

The development of the Digital Factory started in the automotive industry (see SCHILLER, SEUFERT 2002), and further attempts are also being made in the aircraft industry. It can be expected that this new technology will gradually be applied in other industrial sectors as well.

Already existing tools of the Digital Factory are mainly directed towards technical and organisational issues. Their focus lies primarily on procedures for navigating in a virtual building, methods for capacity planning, balancing of production lines and features for animating physical manufacturing processes.

1.2 Micro- and Macro-ergonomic Simulation

Another development approach towards the Digital Factory has its origin in the study of ergonomic, which can be divided into the two different branches of modelling and simulation of humans at work: In a micro-ergonomic view, human postures and body motions are investigated, taking anthropometric and biomechanics basics into account (Figure 1). By using detailed virtual man models, firm insights into the practicability and reasonableness of working tasks shall be gained. Usually, only short-cycled tasks in a spatially limited work system are regarded.

In the macro-ergonomic view, the stress and strain of working humans during longer work cycles are investigated (for the distinction between stress and strain in ergonomics see LANDAU, BRAUCHLER, ROHMERT 1999). Here, specific questions like environmental working conditions during the shift, the personnel structure within complex assembly systems or physiological and psychological stress effects of manufacturing processes are answered. For this application field, personnel-integrated and personnel-oriented simulation tools have also been developed (section 3.1).

Micro- and macro-ergonomic tools should be combined and integrated into the Digital Factory. However, deeper insights show that both kinds of tools are not yet linked to one another. If at all, only micro-ergonomic tools are included in Digital Factory systems. Therefore, a different sets of tools have to be used for macro-ergonomic investigations, causing multiple data input and modelling, each of which have to be done by a different specialist.

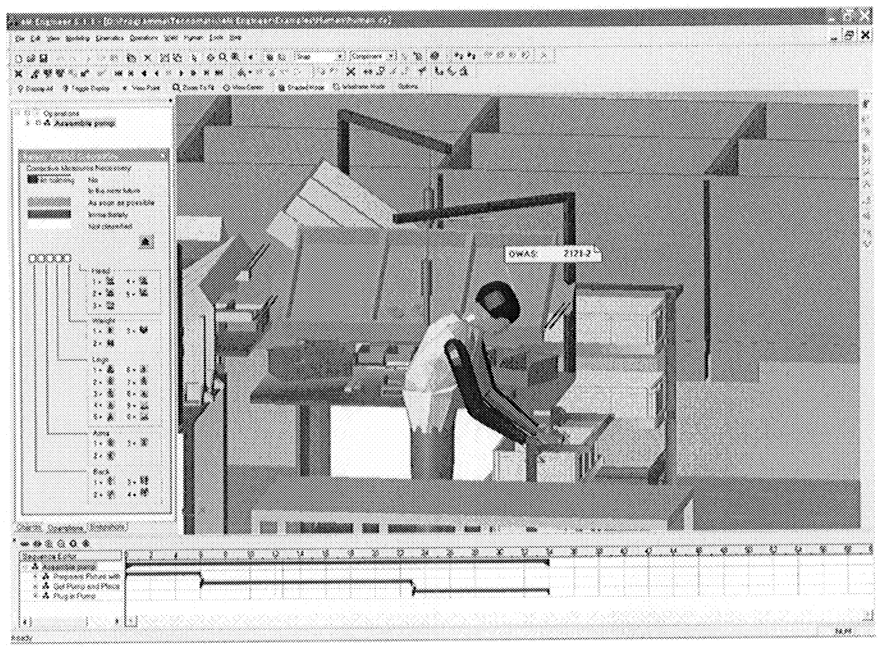


Figure 1. Ergonomic evaluation of a workplace with *eM-Human* by TECNOMATIX

1.3 Vision for Integrating Human Aspects

A prerequisite for overcoming this situation is the development of an adequate data model (see section 4.1). This data model can then serve as a common database for the relevant applications for integrating human aspects into the Digital Factory.

From a micro-ergonomic view, tools for workplace design are needed, such as man models for the verification of human postures and body motions. Such tools are already available (e.g. HALLER 1982 as an early example; *eM-Workplace* from TECNOMATIX 2003). However, these tools are not yet linked to simulation procedures for virtually running the production system in order to evaluate its performance in a production logistics sense (e.g. *Wittness* from LANNER GROUP 2003).

There exists an even more extended vision as to how human aspects should be integrated into the Digital Factory: Beyond well-known anthropometrical and biomechanical aspects of humans, also stress factors, originating either from the work task itself or from the environmental situation, should be prognosticated. Some of these factors, like illumination, can be regarded as constant, while others are influenced by the dynamics of the work process, e.g. the labour energy expenditure. Furthermore, the acoustic noise level as an environmental factor is in first approximation constant, at a certain location, but regarded in the context of a work task of a human with his different locations, it becomes a dynamic factor.

Therefore, from a macro-ergonomic view, the combination of an event-driven simulator for work processes and an evaluator for stress factors is needed in order to prognosticate in the Digital Factory the stress situation of a human during a shift or an even longer working period. Furthermore, the adequate assignment of workers to workplaces and the various forms of their cooperation must be considered. For this purpose, human-centred planning and simulation tools are needed.

2. PLANNING THE PERSONNEL STRUCTURE

2.1 Qualitative and Quantitative Assignment

From a macro-ergonomic view, this leads to the qualitative and quantitative assignment problem. The quantitative problem refers to the number of employees needed in a workshop, while the qualitative problem concerns their possibly divergent qualifications. The starting point for solving this problem is usually given by the pre-defined configuration of the future machinery and equipment of a workshop and a given manufacturing programme which is regarded as representative for a certain planning period. The solution is the personnel structure of the regarded workshop.

With respect to the planning horizon of personnel assignment, different problem areas can be distinguished (Figure 2). The greatest scope of possibilities for the assignment of persons to functions and workplaces in manufacturing systems is found in the case of planning a new factory or in the long-term planning of personnel structures. In this case, the number of employed persons and their abilities can be defined without considering an existing personnel structure. In contrast to the planning of a personnel structure from scratch, the middle-term reorganisation of personnel assignment has to consider the restrictions of an existing personnel structure. In this case, reorganisation means the modification of a personnel structure through training, hiring, and dismissal.

The chosen assignments of workers to functions and workplaces have an important effect on labour costs per manufactured unit and the achievement of logistical and financial objectives. In any case, the aim is to find an optimal transition from the existing personnel structure and to improve the organisational structure by minimising adjustment and personnel costs and maximising logistical goal achievements. New evaluation approaches also include human-oriented criteria (see section 3.2).

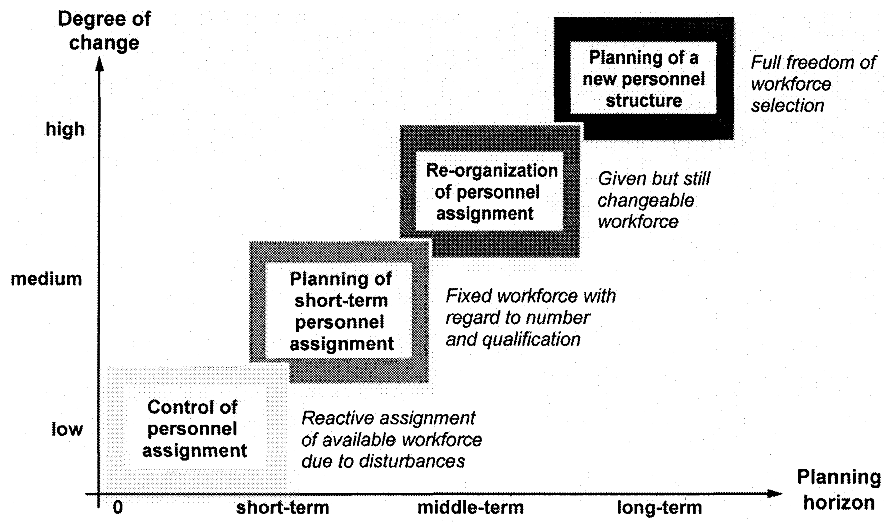


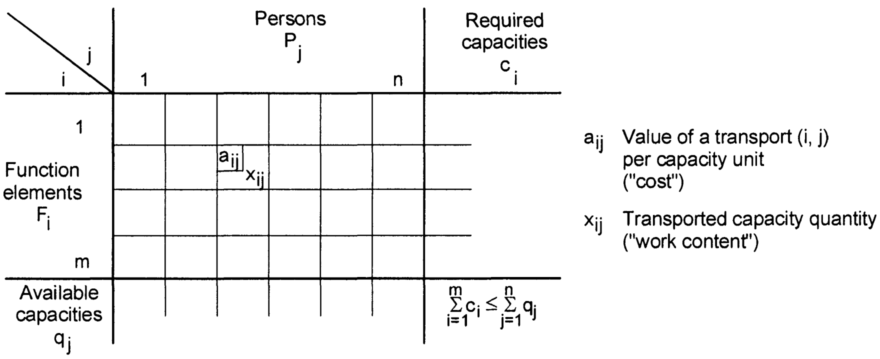
Figure 2. Time horizons for planning and scheduling personnel assignments

Such personnel structure problems can be modelled as a transportation problem, and therefore they ought to be solved by using well-known Operations Research algorithms (Figure 3). However, these algorithms give only a static result, without looking at the dynamics of the production system. The complexity of the problem derives from the numerous events which have to be considered.

There are many other methods for finding an optimal personnel assignment, but none of these incorporate the optimal number-of-workers problem or the optimal staff-skill-composition problem (COCHRAN et al. 1997, pp. 3393). In order to consider the plurality of possibilities for personnel assignments and to exploit the flexibility of human resources, effective planning tools are needed to solve such planning problems. For the time being, the problem can only be solved by investigating various scenarios and evaluating them with an appropriate simulation tool.

2.2 Simulation as an Evaluation Tool for Scenarios

For planning and evaluating potential personnel assignment solutions, the ifab-Institute of Human and Industrial Engineering of the University of Karlsruhe exploits the possibilities of using simulation as a planning tool. Figure 4 shows the general structure of one of them, namely *FEMOS* (German abbreviation for "Manufacturing and Assembly-Simulator"). Dependent upon the type of personnel assignment problem, various other simulation tools have been developed. Some of them are closely connected with planning games for educational purposes (ZÜLCH, BRINKMEIER 1995).



Goal function: $Z = \sum_{i=1}^{m} \sum_{j=1}^{n} a_{ij} \cdot x_{ij} \Rightarrow \text{opt}$

Constraints: $\sum_{j=1}^{n} x_{ij} = c_i$ ... required capacities

$\sum_{i=1}^{m} x_{ij} \leq q_j$ ... transport quantity

$x_{ij} \geq 0$

Decision class: P, solvable with polynomial effort $O(k^2, q)$, with $k = \max(m, n)$ and $q = \sum_{j=1}^{n} q_j$, if c_i and q_j are integer

Figure 3. Modelling a personnel structure as a transportation problem (following ZÜLCH 1996)

All these procedures posses the same general approach to model personnel qualifications (ZÜLCH 1995, pp. 114): Different functions - meaning a set of similar activities - which are defined in the manufacturing programme have to be assigned to machines, or more generally to machine or workplace groups or even only to departmental units. Hence, there exists a relation between these functions and machines, which is referred to as feasibility. Every function requires a person or, more generally, a personnel type for its fulfilment, so that at least one person must be able to do this job. This relation is called ability/requirement. As a third relation, this person must be competent on the machine on which the job is performed. Hence, there are three relations connecting a function, a machine and a person which establish one qualification element of this person.

In order to model these relations, the simulation tool *ESPE* (German abbreviation for "Bottleneck-oriented Simulation of Personnel Structures") uses a so-called function-equipment-matrix (Figure 5). This matrix contains all needed functions as rows and the already set configuration of machines as columns. The matrix elements contain all function elements which appear in the production programme and which should be operated at the given machines or manual workplaces. Assigned to a person or personnel type, they are called qualification element (see the grey elements of the matrix). Usually, a set of function elements is assigned to a single worker or type of worker; this is then the qualification of this person or personnel type. As important logistical information, this matrix also contains the needed capacity for machines and personnel in the modelled workshop.

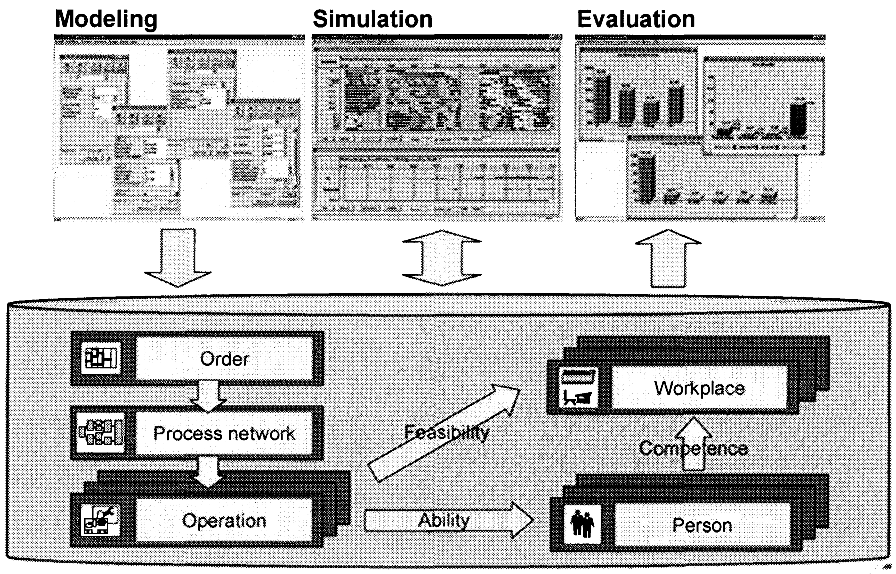


Figure 4. Components of the simulation tool FEMOS (following ZÜLCH, BRINKMEIER 1995, p. 94)

The mentioned simulation tools *FEMOS* and *ESPE* are discrete, event-driven, deterministic simulators with the possibility to model stochastic events like machine disturbances and personnel absenteeism. The given manufacturing programme consists of orders which are modelled as activity networks. Beyond the possibility to model various kinds of personnel assignment, these simulators also allow for changes related to the intended order programme of a workshop as well as for the reconfiguration of the machinery equipment. Thus, various scenarios can be investigated in a simulation study.

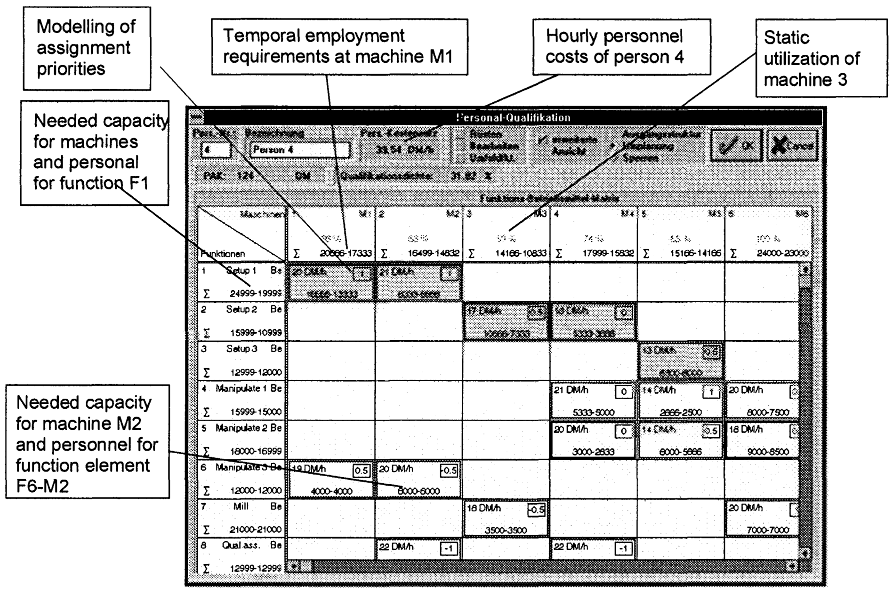


Figure 5: Function-equipment-matrix in the simulation tool *ESPE* (following HEITZ 1994, p. 112)

3. SIMULATION OF HUMAN ASPECTS

3.1 Distinction between Personnel-integrated and Personnel-oriented Simulation

In order to clarify the principles of human-centred simulation, the Association of German Engineers (Verein Deutscher Ingenieure - VDI) published a guideline for the modelling of personnel in simulation models (VDI 3633, part 6, 2001; ZÜLCH, VOLLSTEDT 2000). This guideline concerned with applications in the field of production and logistics only. With respect to the degree of detail in human models, different kinds of simulator are distinguished. The related tools are divided into personnel-integrated and personnel-oriented simulators. Personnel-integrated simulation tools regard the significant properties of the staff employed in production and logistics systems. Their main focuses are applications, in which interactions between workers and machines play an important role.

There are some minimum requirements which personnel-integrated simulation models and tools have to fulfil: First of all, a distinction between the capacities of the personnel and the machines must be possible. Figure 6 shows the animation output of a Gantt-chart which contains these different views of machines and persons.

Furthermore, the determination of the effects of changed work structures, e.g. the personnel capacity requirements for a multi-machine operation or for production cells, must be possible. Therefore, personnel-integrated simulation tools have to offer features for modelling co-operation and group work. Additionally, individual modelling of the working times of the personnel and the operation times of the machines is a main prerequisite for a personnel-oriented simulation tool.

Compared to personnel-integrated simulation tools, personnel-oriented simulators possess a higher degree of detail for answering special human-related questions. Here, the analysis of certain organisational forms and work conditions with respect to the related effects on the production processes and outputs are of particular interest.

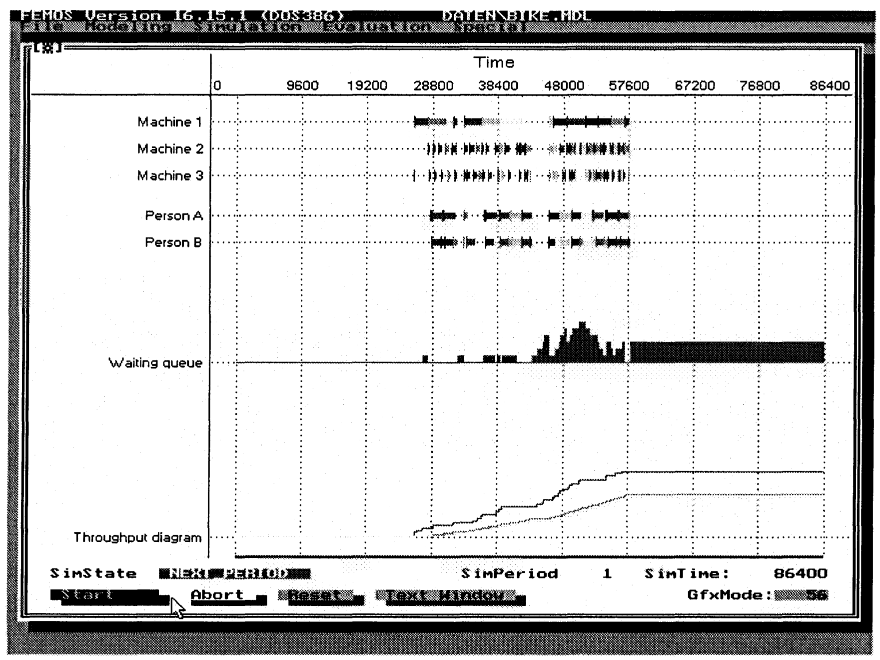


Figure 6. Gantt-chart of order processing, waiting queues and throughput-diagram of a production system in the simulation tool *FEMOS*

For example, emphasis may be put upon on the analysis of the work load and stress for humans, the over- or under-utilisation of workers, learning and unlearning effects, or even the human reliability depending upon the workplace design and work organisation. In comparison to personnel-integrated simulation, these tools require additional information about the work tasks, the environmental conditions and the characteristics of the modelled personnel.

3.2 Human-centred Evaluation

Personal-oriented simulation tools should be used if the effects of human behaviour on the logistical performance of the production system are a central point of interest. This may concern logistical key data like production output, utilisation of resources, lead time degree or tardiness of orders. Furthermore, financial aspects may also be of interest, especially manufacturing costs and process costs.

Beyond this, human-centred evaluation criteria may be used in order to characterise the working conditions for the individual workers or type of worker under investigation. Examples of such studies from an ergonomic point of view are (see VDI 3633, part 6, pp. 7):

- the staff work load with respect to the capacity demand,
- the physiological stress with respect to the working times system,
- the individual energy expenditure, dependent upon the performed activities and the occupied work posts,
- the influence of the qualifications of a worker on his human error probability,
- the degree of overstrain, fatigue, monotony and wear-out dependent upon the performed work tasks, and
- the sequential completeness of performed tasks, i.e. their coverage of planning, operating and controlling aspects.

Even from an industrial sociology point of view, investigations questioning the autonomy, decentralisation and integration of tasks within a departmental unit become possible (Figure 7). Most of these criteria seem to be reasonable, but, from a scientific perspective, a broad field of studies for their validation is opening up.

4. PROGNOSIS OF HUMAN ASPECTS IN THE DIGITAL FACTORY

4.1 Object-oriented Data Model

Some of these modelling and evaluation approaches are ready to be integrated into the Digital Factory. However, the amount and complexity of data and methods demand an adequate system for production data management. The critical question as to which data base architecture is the right one to guarantee consistency, actuality and flexibility for expansion, beyond all the other criteria of data management.

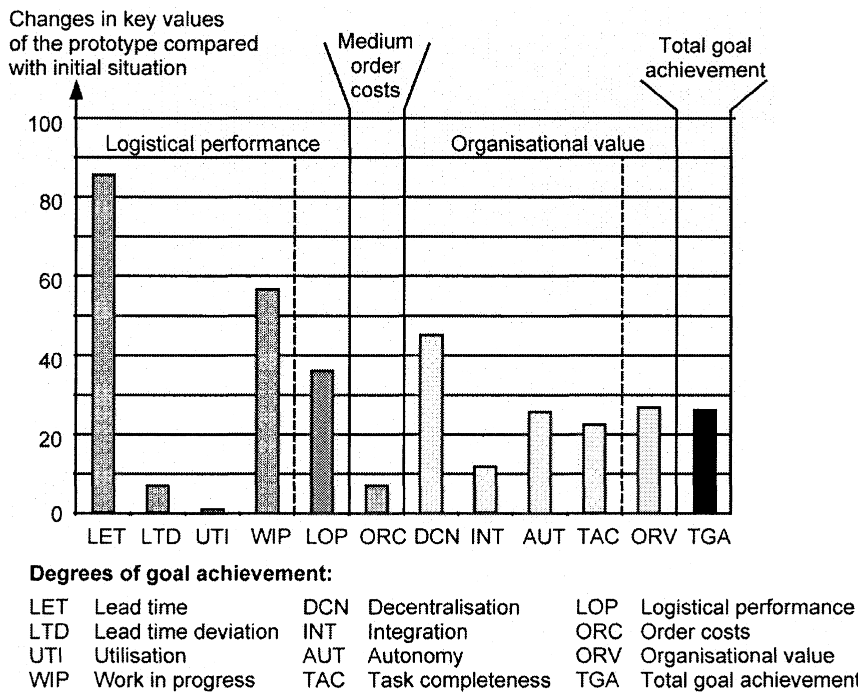


Figure 7. Simulation results of organisational changes in a mechanical component production (following BRINKMEIER 1998, p. 221)

A feasible path can be seen in object-oriented modelling techniques and related tools like *UML* (Unified Modelling Language; FOWLER, SCOTT 1999). The basis of the approach presented here is an object-oriented Product/Production Model. This data model has been developed as basis for the integration of various tools for product design, planning of production systems and operations planning in parts production (ZÜLCH, BRINKMEIER 1998).

4.2 The Information and Planning System *ADAMO*

As a pilot system for the integration of human aspects into the Digital Factory, the ifab-Institute of Human and Industrial Engineering of the University of Karlsruhe is developing a workshop modelling and evaluation tool called *ADAMO* (German abbreviation for "Arbeitsschutzdaten-Modellierer"; KELLER 2001, pp. 142). This information and planning system is designed to incorporate aspects of occupational health and safety (OHS) in the CAD-representation of a workshop.

The pilot system is based on the abovementioned object-oriented database-structure in which the objects of a workshop, together with their OHS-relevant attributes and applicable calculations and visualisation methods, are stored. The integration of calculation methods in this database has been supported by the use of sequence-diagrams. As a first application, prognosis methods for acoustic noise and illumination were implemented (Figure 8) and produced promising results (KELLER 2001, p. 161).

The integration of human aspects into the Digital Factory has just started and is yet producing a number of questions and problems. However, the goal is clear:

- A comprehensive tool for factory planning,
- offering consistent, redundancy-free data processing,
- which delivers human-related prognoses data,
- beyond the already well-known production logistics and cost-related key figures.

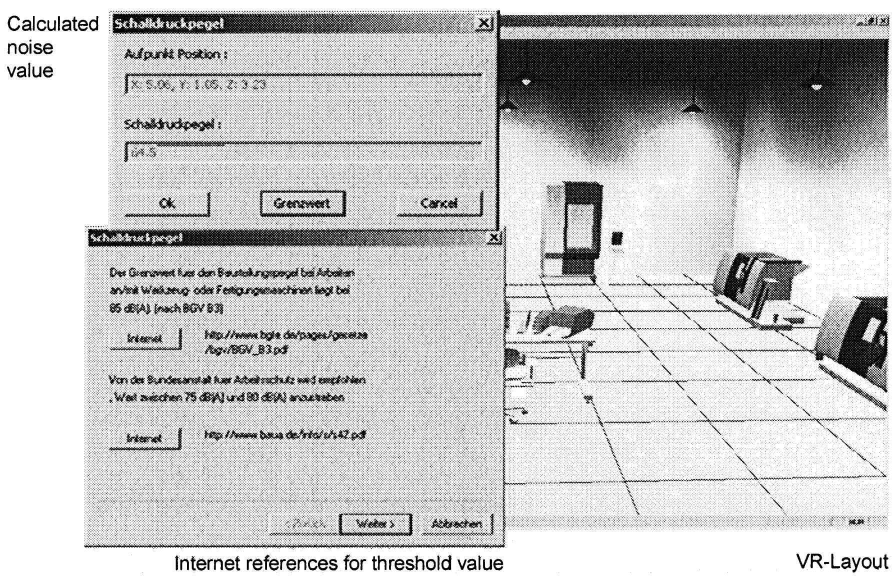


Figure 8. Calculation of the acoustic noise level and the respective threshold value in the OHS-planning tool *ADAMO*

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