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THE CONTRIBUTION OF ERGONOMICS IN IPD-PROCESSES

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ABSTRACT

Besides engineering design and industrial design, ergonomics is a core domain in Integrated Product Development. A crucial objective in ergonomic product design is man-machine compatibility, regarding physical and psychological (mental, cognitive) characteristics of users. For both aspects – physical and psychological – approved methods of analysis and design are available. Some of these methods are described as examples.

1 ERGONOMICS IN INTERDISCIPLINARY PRODUCT DEVELOPMENT PROCESSES

Today, the development of products is conceived as an interdisciplinary and dynamic process. To achieve optimal results in product development, a holistic perspective within an interdisciplinary approach is essential. Engineering design, industrial design, and ergonomics all play their specific roles in this endeavour. This is necessarily so, because the user perceives and interacts with the product in a holistic way.

In this holistic perspective, different foci are addressed: The technological-functional characteristics of the project (the product performs as required by the task at hand – or not), the esthetical features of the product like shape, colour, surface, material, sounds or smells, leading to a subjective assessment (the product pleases – or not), and the ergonomic and psychological characteristics of the human-product interface, governing effectiveness and user-centeredness of the product (figure 1).

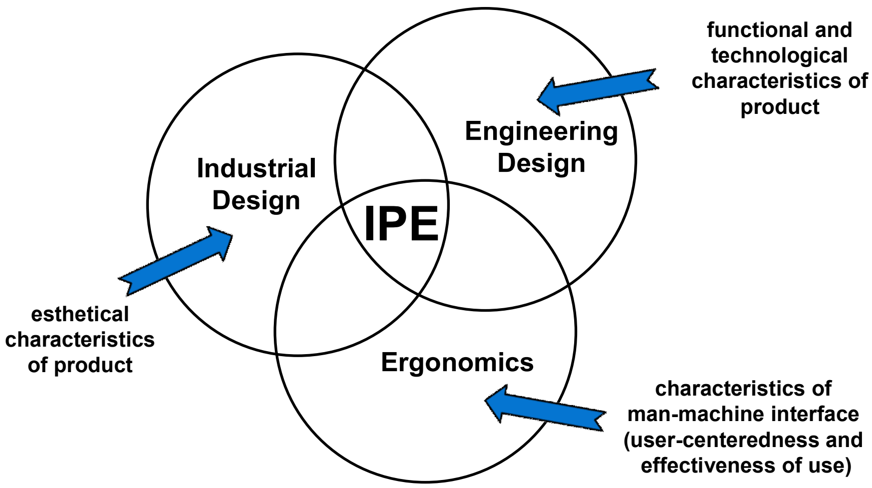


Figure 1: Product design in an interdisciplinary approach

To achieve a holistic, ‚optimal' product in IPD processes, ergonomics should play a substantial role from early analysis and design phases on. An 'end of pipe' approach to ergonomics design, trying to correct design flaws in late phases of product development, is not likely to yield products with satisfying usability characteristics.

2 CONTENT, OBJECTIVES, AND FOCAL ISSUES OF ERGONOMIC PRODUCT DESIGN

The content of ergonomic design is determined by the diversity of human traits and capabilities, and their appropriate use. In this context, 'appropriate use' means a broad, comprehensive, and effective use of these capabilities, while respecting their limits.

Using ergonomic expertise, products can be designed in a way to protects users´ health and to take full account of users´ characteristics, traits, and capabilities, thus promoting user performance and satisfaction. Especially in saturated markets, these product features may constitute a competitive edge.

In 2000, the German Ergonomics Association (Gesellschaft für Arbeitswissenschaft e. V.) set up a memorandum regarding the future of work („Die Zukunft der Arbeit erforschen" – Investigating the Future of Work). In this text, ergonomics is identified as most crucial factor for product competitiveness. In the memorandum, three approaches are distinguished:

- The **user-centeredness of products** is a core aspect of innovation, a decisive feature for product marketing, and a challenge for **product ergonomics** und ergonomic research.
- Ergonomic design of tools – as specific products – is a prerequisite for **human-oriented design of workplaces,** and thus for effective use of corporate human resources.
- The growing demand for **experts in product ergonomics** has to be matched by new **educational frameworks and programmes**, especially for engineers.

According to our experience, this means to empower engineers to understand the ergonomic problems affected by their work and the results of their work, to solve routine problems in this domain by themselves, and to cooperate with ergonomics experts from different disciplines and educational backgrounds.

This applies equally to product engineers, concerning product ergonomics (product design), and production engineers, regarding issues of production ergonomics (workplace and work process design).

In the relevant literature, and in discussions within the scientific community, several definitions and descriptions of ergonomics and ergonomic design objectives are used.

As a simple and practical approximation, ergonomics can be described as a scientific discipline engaged in adapting work to the worker and products to the user. This adaptation implies the optimisation of

- effectiveness of product use (performance, productivity),
- health, safety, and well-being of product users, and
- ease of use, usability, and user-centeredness.

These three criteria are to be perceived as belonging together in a complementary way.

Decisions in ergonomic product design are – as any design decisions – subject to cost-benefit considerations. The respective benefit is to be generated from an effective use of human capabilities. Thus, comfort and well-being are no paramount objectives in themselves. Also, the minimisation of stressors in working situations is no unconditional objective of ergonomics.

Ergonomic product design encompasses the following focal issues:

- The design or shape of the product should reflect or ‚materialise' the product´s characteristics regarding its use.

- The product needs to be adapted to the users´ anthropometric characteristics.
- The product needs to be adapted to the physical characteristics of the users (biomechanics, movement dynamics, required forces).
- The product needs to be adapted to the psychological characteristics of the users (perception, cognitive processes, learning styles).
- Aspects regarding safety in using the product need to be considered in design processes.

Despite different methodologies, the domains of industrial designers and ergonomists, respectively, tend to overlap, regarding these issues. This should not be perceived as a source of conflict, but rather as an opportunity for cooperation. Cooperative design processes integrating engineers, industrial designers, and ergonomists are prerequisites for optimal design solutions.

In the list of focal issues described above, two crucial aspects are evident, both relating to the ergonomic objective of compatibility. In this context, compatibility refers to the best possible 'fit' between the characteristics of the product or tool on the one hand, and human physical and psychological characteristics on the other.

The methodologies established in ergonomic design research and practices can be categorised according to this distinction, focussing either on physical or psychological aspects of compatibility. In the following, some selected methods are discussed, according to this distinction. In a first section, digital human models are introduced as prototypical tools employed to improve physical compatibility. Thereafter, a methodology addressing psychological (especially cognitive) compatibility will be presented.

3 SELECTED METHODS OF ERGONOMIC DESIGN REGARDING PHYSICAL AND PSYCHOLOGICAL MAN-MACHINE COMPATIBILITY

3.1 Physical compatibility: Digital human models in ergonomic product design

3.1.1 Applications and advantages

Digital human models are computer-based models of human beings. They are used to tackle various ergonomic design problems in industry, research, and education. They incorporate expertise regarding anthropometric and biomechanical characteristics of the intended product users, and allow for interactive visualisation of products in situations of use, including realistic representations of the users. They are used as tools for ergonomic analyses, focussing on anthropometrics and biomechanics, and support optimisation of the product´s ergonomic features as well as the work processes regarding manufacturing and maintenance of these products.

All available digital human models require a considerable amount of ergonomic expertise and experience from their users. Without this expertise and experience, design flaws are likely to remain undetected. In this case, there is a risk of digital human models being employed to legitimise faulty analysis or design results on a pseudo-scientific basis. This is likely to have severe consequences, especially if these results are to be used as ergonomic foundation for a product´s introduction into the market.

In industrial product development processes, engineers or industrial designers frequently need to cover ergonomic aspects as well, in addition to their core tasks, without being adequately educated in ergonomic theory and methodology. In this case, digital human models are to provide a maximum of methodological support and guidance for their users. Thus, these systems provide expert knowledge and a transparent user guidance. Nevertheless, engineers and industrial designers using these systems in practical design processes should be prepared to consult ergonomics experts when confronted with limits regarding their own knowledge and skills, while at the same time remaining within the design process.

Digital human models are used in product ergonomics as well as production ergonomics. At the core of these systems are digital biomechanical human models, which can be situated by the users in virtual (working) environments. The behaviour of the models is analysed regarding the respective tasks or activities. Thus, users can assess what the models can see, if they are in a convenient and comfortable environment, what they can reach with their hands or feet, how they might be injured, or when they are likely to become tired. In this way, the user is supported in designing safe, comfortable and user-centred products

3.1.2 Examples of digital human models

a) Tecnomatix Human Performance

Tecnomatix Human Performance can be used to assess product designs, regarding e.g. if future users will be able to visually perceive in an appropriate way, can reach the controls easily, and will have the strength to operate the product conveniently and safely. An 'occupant packaging toolkit' helps to improve, as an example, ergonomic features of the interior designs of vehicles and airplanes.

Jack/Jill

The human modelling system Jack was developed at the University of Pennsylvania, USA (figure 2). The models Jack (male) and Jill (female) are to support corporations in various branches in developing effective and safe products in an efficient way, regarding required time and budget. Additionally, Jack/Jill can also be used to design manufacturing plants and work processes, optimising productivity and employee safety.

(http://www.ugsplm.de/produkte/tecnomatix/human_performance/jack/)

Figure 2: Examples of digital human models (Tecnomatix)

eM-Human

eM-Human is a virtual environment for the interactive design and optimisation of manual tasks. The planned work process can be defined in a 3D model of the real production setting, employing a virtual human model. A broad functionality supports detailed analyses of the workplace, taking into account work cycles and ergonomic characteristics of the specific environment. Each modification to the design can be assessed immediately, so that the industrial engineer is enabled to optimise the work system before physical implementation.

(http://www.ugsplm.de/produkte/tecnomatix/human_performance/em_human.shtml)

b) Safework (Human Modeling Technology)

Safework is a 3D human model for ergonomic analyses and the design of workplaces (figure 3), developed by GENICOM (Montreal, Canada). This development was supported by the French and Canadian armed forces.

Safework is available

- as stand-alone version SAFEWORK® Pro™,

- integrated in Catia,

- as a DELMIA link,

- integrated in Division/proE

Figure 3: Examples of digital human models (Safework)

<u>SAFEWORK® Pro™</u>

SAFEWORK® Pro™ is one of the most advanced human models for detailed and accurate analyses of the human-machine interface. SAFEWORK® Pro™ supports designers in various domains (e.g. aeronautics, automotive, consumer products) in following a human-centred approach from task design through to final tests of product functionality. A sophisticated human model is combined with an intuitive user interface and a comprehensive set of analysis tools, making SAFEWORK® Pro™ a tool to be used across the whole product development process.

<u>SAFEWORK® in CATIA</u>

The integration of SAFEWORK® technology into the CATIA Portfolio (first version scheduled for CATIA V5 R6) allows the user to combine the features of the human model with CATIA product development tools. As a consequence, products and workplaces can be designed for maximum quality, effectiveness, and efficiency, while at the same time enhancing safety and reducing costs caused by accidents and other factors influencing users´ health.

<u>DELMIA/SAFEWORK Link</u>

The connection between DELMIA and SAFEWORK allows using human models across the whole product development process, including simulations run in the DELMIA environment. Users can generate detailed human models in SAFEWORK® and insert these models seamlessly instead of ENVISION/ERGO™ human models, before using the 'task-oriented' functionality of ENVISION® and IGRIP®. With DELMIA/SAFEWORK®, users can employ the powerful simulation features of ENVISION/ERGO™ like e.g.:

- RULA (Rapid Upper Limb Assesment),
- NIOSH (National Institute of Occupational Safety and Health),
- MTM (Methods Time Measurement), and
- Specification of limits regarding e.g. maximum weights to be lifted.

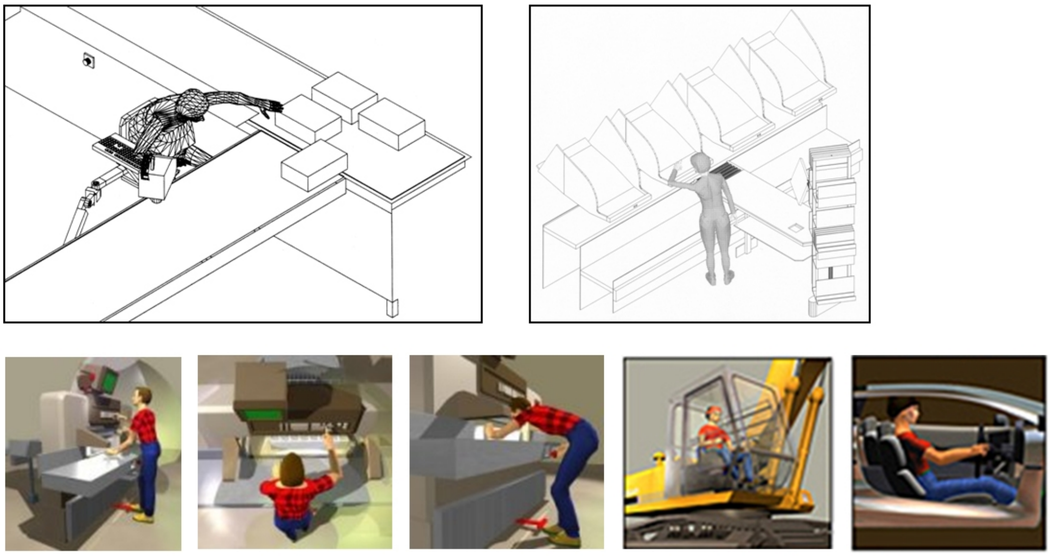
<u>Integration in Division/ProEngineer</u>

PTC (Parametric Technology Corporation) also chose SAFEWORK® technology for human modelling. The DIVISION SAFEWORK® Manikin (DSM) and the Manikin Builder Option (MBO) allow users of DIVISION MockUp visualisation software to integrate SAFEWORK® human models into their designs.

c) ANTHROPOS

The human model ANTHROPOS was developed by IST-GmbH (Gernsheim, German; now merged with Tecmath, Kaiserslautern). ANTHROPOS is specifically tuned for engineering design and visualisation. CAD-ANTHROPOS is integrated into several CAD systems for personal computers, like CADKEY und AutoCAD, or workstations, like CATIA und CADDS (figure 4).

ANTHROPOS



(http://www.human-solutions.com/automotive_industry/news_report_de.php?id=3)
(http://www.gallery-diabolus.com/MAPPE1/)

Figure 4: Examples of digital human models (ANTHROPOS)

The most recent ANTHROPOS update (V. 5.2) for CADKEY/WIN-NT was released in the late 1990ies. After merging with Tecmath Kaiserslautern, the development of ANTHROPOS was discontinued. The developers left the company.

(http://www.gallery-diabolus.com/MAPPE1/)

Mainly for visualisation purposes, the following tools were developed: *Architektur*-, *Design*- and *Charakter*-ANTHROPOS, and the visualisation and ergonomics system ANTHROPOS ErgoMAX for the 3D StudioMAX platform.

(http://www.human-solutions.com/automotive_industry/news_report_de.php?id=3)

d) IDO:Ergonomics

IDO:Ergonomics is an interactive ergonomics simulation system, developed by IC:IDO in Stuttgart, Germany (figure 5). It offers designers a human model suitable for addressing ergonomic issues in early design phases – before the realisation of a physical prototype –, based on 3D data. In this way, time and costs can be saved in product development. Employing the virtual human, controls, displays, and visual arrays can be assessed regarding anthropometric and other ergonomic criteria.

IDO:Ergonomics - Interactive Ergonomic simulation system

(www.icido.de/de/Produkte/VisualDecisionPlatform.html)

Figure 5: Examples of digital human models (IDO:Ergonomics)

e) RAMSIS

RAMSIS is an acronym for ‚**R**echnergestütztes **A**nthropometrisch **M**athematisches **S**ystem zur **I**nsassen-**S**imulation' (computer based anthropometric mathematical system for occupant simulation).

RAMSIS was developed by Tecmath (Kaiserslautern, Germany), supported by the German automotive industry (figure 6). RAMSIS is mainly used for the ergonomic design of vehicle interiors and cockpit environments. Today, more than 70% of all car manufacturers worldwide employ RAMSIS. Furthermore, RAMSIS is completely integrated into the eM-Human environment, allowing for assessment and optimisation of assembly processes in the production planning phase.

(http://www.human-solutions.com/automotive_industry/ramsis_de.php)

Figure 6: Examples of digital human models (RAMSIS)

3.1.3 Application in industrial research and IPD projects

Academic education receives vital input from ergonomic practice. Therefore, some applications of ANTROPOS in solving practical problems will be mentioned briefly. All these applications relate to very specific ergonomic problems. These examples are:

- the prevention of stresses in the hand-arm system caused by unsuitable joint positions (joint end positions), regarding master-slave manipulators (figure 7),

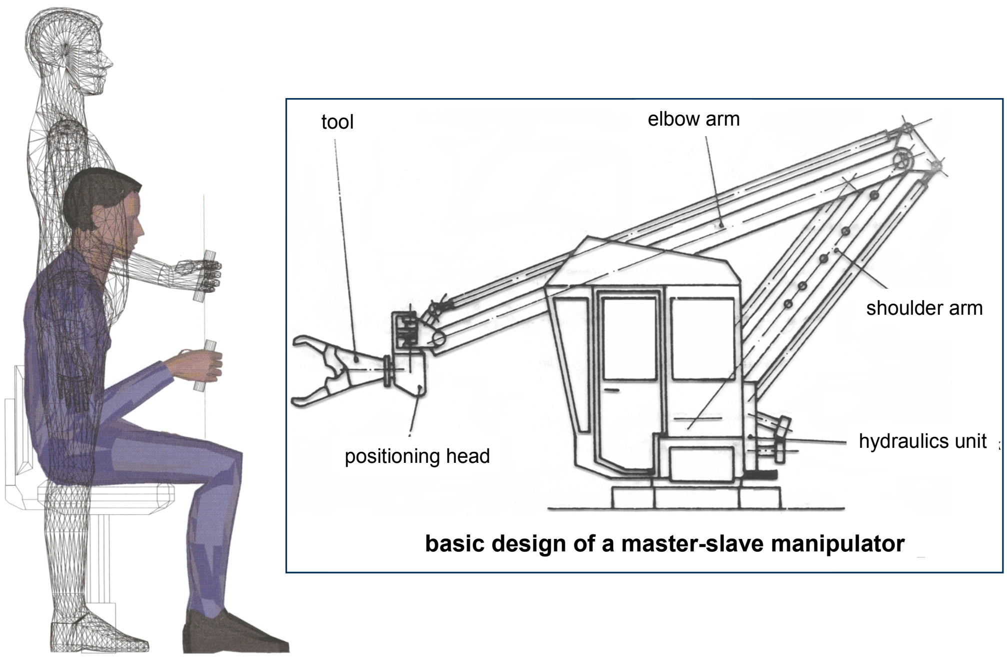


Figure 7: Prevention of stresses (joint end positions) in hand-arm system regarding master-slave-manipulators

- the development of flexible airbag assembly systems in modular design (figure 8),

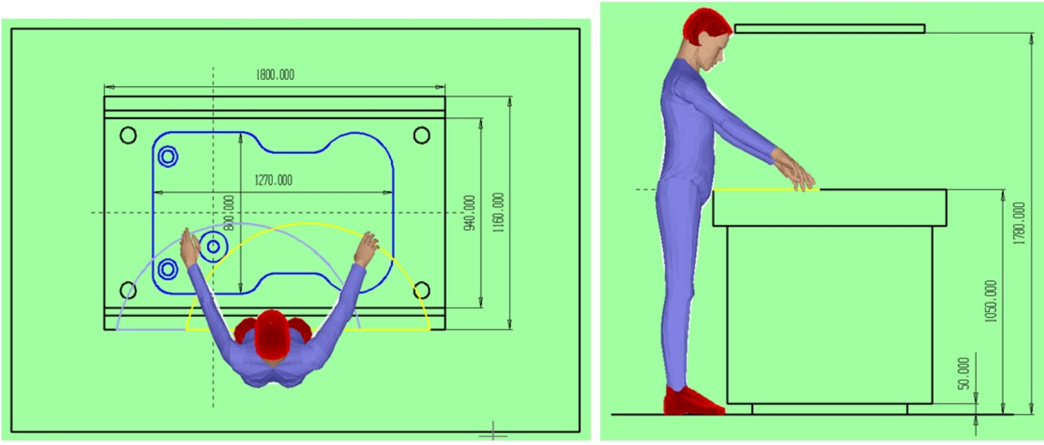


Figure 8: Development of flexible airbag assembly systems in modular design

- the re-design of packing workplaces after the introduction of new packing materials (cf. figure 4) and
- the assessment and re-design of workplaces in mail distribution centres (cf. figure 4).

In the following, examples of students´ projects are presented. These projects were performed during their participation in Integrated Product Development (IPD) study programmes. In these projects, ANTHROPOS was used to examine ergonomic issues:

- Wheelman (figure 9)

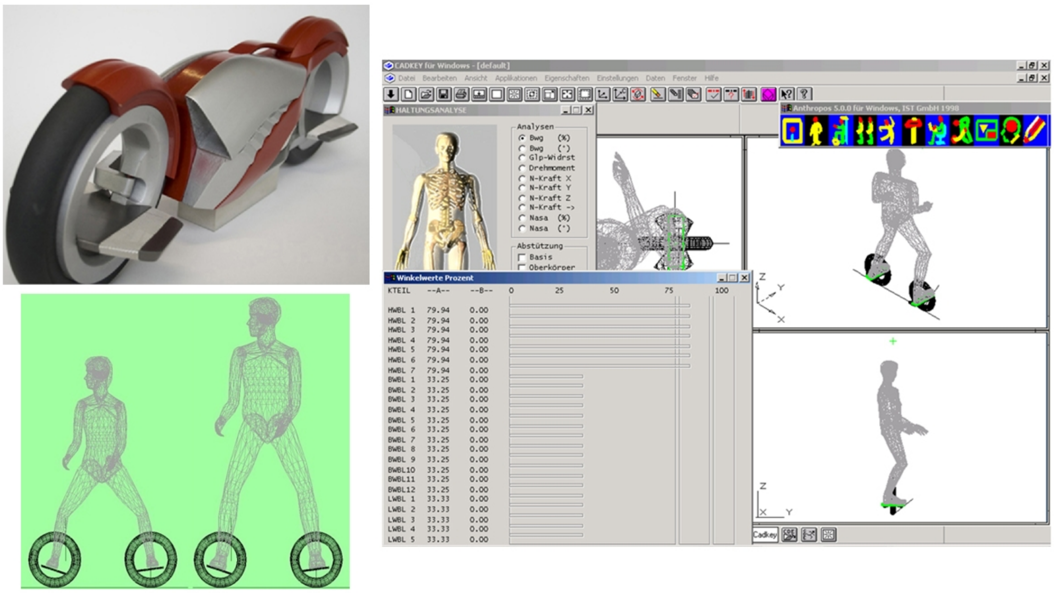


Figure 9: Wheelman

- Foldable sleigh (figure 10) and

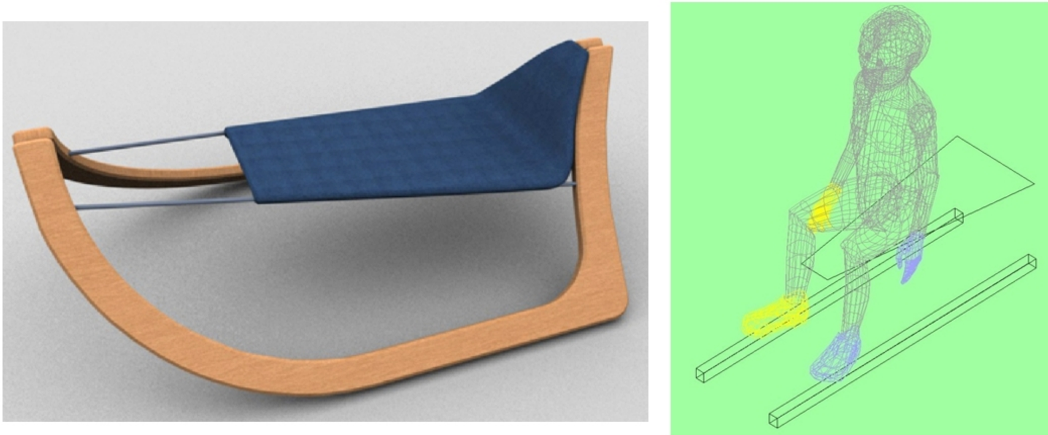


Figure 10: Foldable sleigh

- Ski grinding device (figure 11)

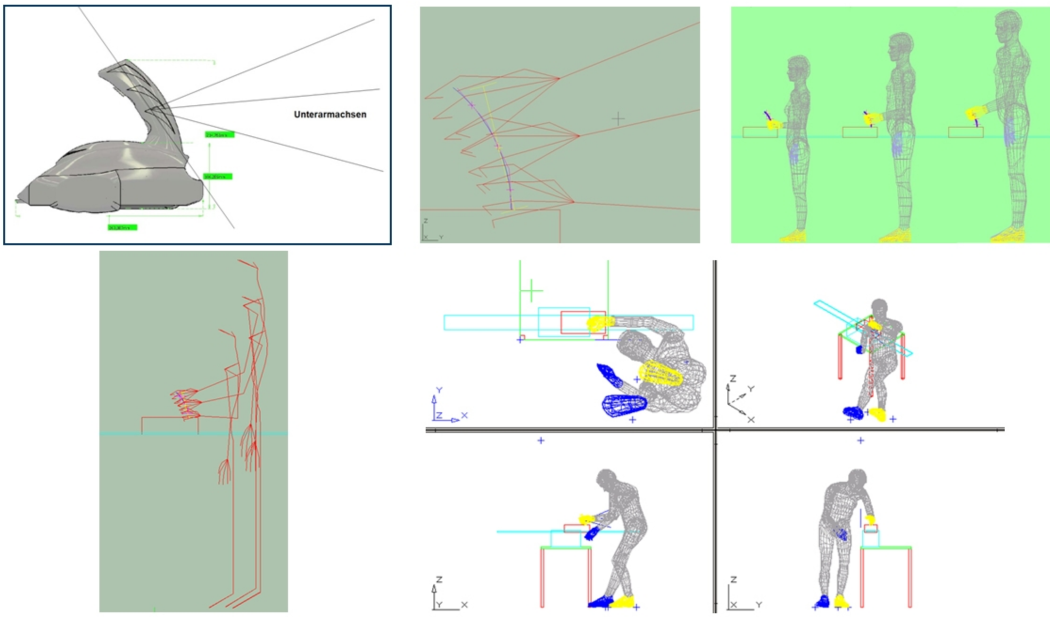


Figure 11: Ski grinding device

3.2 Cognitive compatibility of human-machine interfaces

Theoretical and methodological approaches to investigate cognitive compatibility, and to design the human-machine interface accordingly, can be based on theories from cognitive psychology, concerning mental models (Johnson-Laird, 1983; Hartmann & Eberleh, 1991; Hartmann, 1995, 2002).

This theoretical approach is suitable for analysing conceptional models 'behind' the design of man-machine systems, and the mental models of the users, and for comparing these two types of models. From the analysis of users´ mental models, valuable hints can be derived for the (re-)design of man-machine interfaces.

The theory of mental models (e. g. Gentner & Stevens, 1983; Johnson-Laird, 1983; Hartmann & Eberleh, 1991; Hartmann, 1995, 2002) relates to the structure of human knowledge about the world. Mental models are conceived as analogue – as opposed to linguistic (language-based) or symbolic – types of knowledge. According to the advocates of mental models, this form of knowledge is the basis for all knowledge phenomena, including linguistic/symbolic knowledge. Hartmann and Eberleh (1991) – based on earlier work by Johnson-Laird (1983) – propose six types of physical mental models and two types of conceptual mental models. Physical mental models relate to the physical world in an analogue fashion, whereas conceptual mental models connect physical mental models to linguistic knowledge. Physical mental models can be arranged in a matrix with the dimensions 'spatial structure' and 'temporal structure' (figure 12). Regarding spatial structure, topological and metric models are distinguished. Topological models represent non-metric relations, like 'is-a-part-of' or 'is-neighbour-of'. Distances between and sizes of objects are not represented.

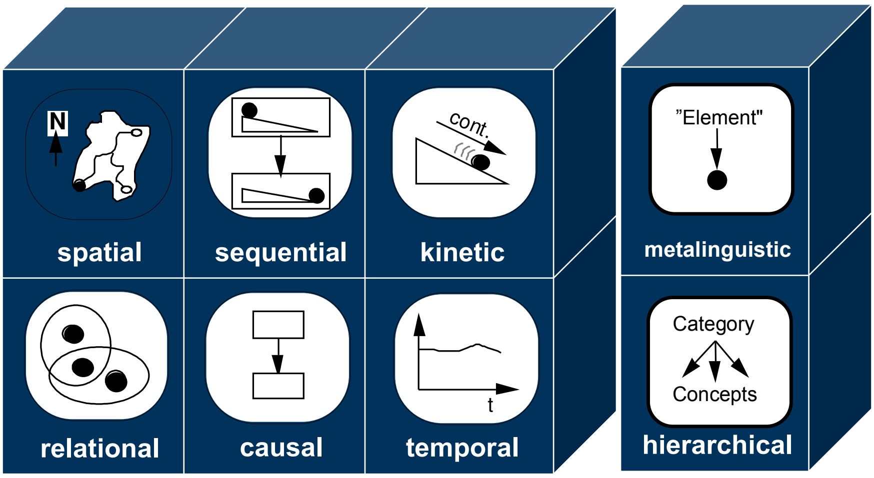


Figure 12: Taxonomy of mental models

The topological models can be specified as follows:

- Relational models contain elements representing objects of the real world. Relations between these objects represent relations between the according real-world objects. Metric properties of the real objects and their relations are not represented. An illustrative example of a relational model is an organisation chart of a company, representing hierarchical relations between organisational units, but no metric distances between these units in the real-world company.
- In causal models, several discrete points in time can be represented, in addition to the features of relational models, like it is done in schematic flowcharts.
- Temporal models depict (quasi)-continuous processes in time. An example: A thermometer displays outdoor temperature, without specifying where exactly – in a metric sense – ,outdoor' is, where the point of measurement is located.

The metric models have the following properties:

- Spatial models are (usually two- or three-dimensional) representations of the perceived world. Unlike topological models, the metric properties of the real world (sizes, distances, proportions etc.) are preserved. (Mental) maps may be regarded as examples.
- Sequential models arrange a set of spatial models in a temporal sequence. A good example is a comic strip.
- Kinetic models depict continuous processes based on spatial models, like in a 3D computer simulation of manufacturing processes.

Conceptual mental models connect analogue knowledge entities to linguistic labels and structures:

- Metalinguistic models relate analogue representations to linguistic labels like e.g. names.
- Hierarchical models allow the representation of concept hierarchies (e. g. concept "saws", category "tools").

In ergonomic product design, this taxonomy serves two purposes:

- In the analysis phase, the taxonomy is used to identify and describe the types of mental models typically employed by the users, regarding the tasks to be performed or activities to be undertaken with the tool or product under consideration.
- In the design phase, the taxonomy serves as a Morphological Box (Zwicky Box) to generate variants of the human-machine interface, taking into account the mental models of the users, as previously investigated.

In the analysis phase, data are typical gathered by observation-interviews with (prospective) users in realistic work settings, whilst using those a-priori products to be re-designed or replaced by the respective product development process.

The application of the taxonomy in the design phase is illustrated by a real-world case from the domain of production technology. In this design project, the paramount objective was to develop a learning-friendly CNC controller and programming system, specifically suited for skilled workers.

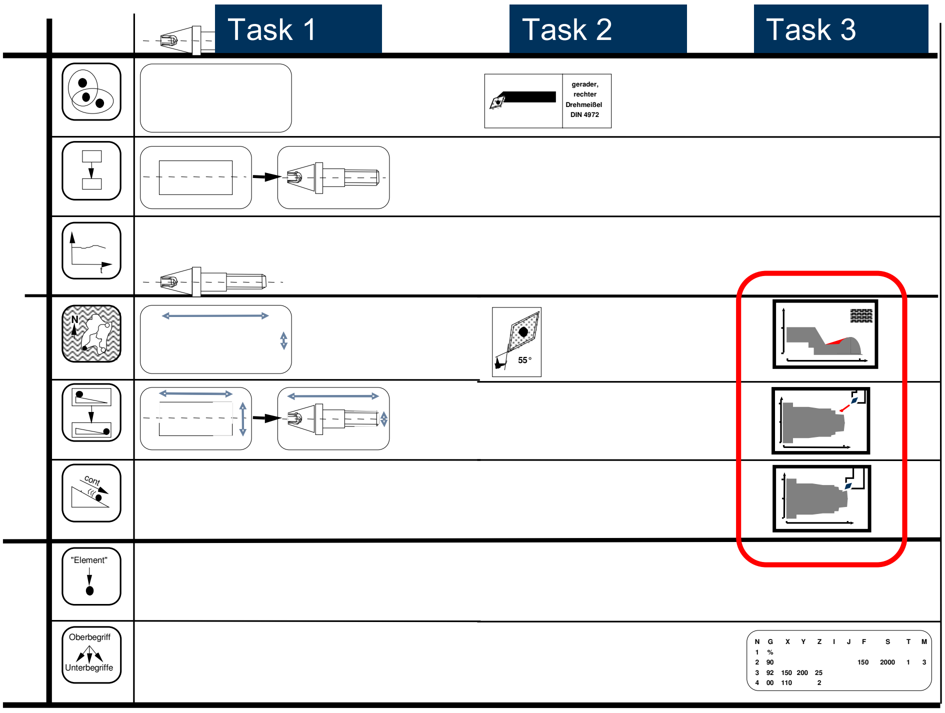


Figure 13: Design space

In figure 13, a highly simplified extract from the design space used in this project is depicted. This design space has two dimensions: Mental models (vertical), and tasks of the users typically performed using the product under consideration (horizontal, only some aspects of the real design space depicted in figure 13).

In the design space, variants of man-machine interfaces regarding these different tasks are developed, each one being an implementation of a specific mental model relating to the respective task. For each task, the number of developed variants is usually much smaller then the number of mental models. On the one hand, this is because some mental models tend to be not suitable – as a matter of principle – for given tasks (e.g. static models for tasks implying process simulation). On the other hand, there may be results from the analysis phase indicating that some types of models are not compatible with the mental models actually employed by the intended users.

Conversely, there is usually more than one design alternative. This may be because information from the analysis phase is incomplete or not sufficiently accurate to identify one favourite design alternative. This may also be because different users tend to use different types of mental models, depending e.g. on educational background or degree of expertise. Moreover, one single user may use different mental models at different times, depending on e.g. situation parameters (speed vs. accuracy requirements, etc.). In these cases, several design alternatives for the same task may need to be developed, tested, and even implemented, as alternative modes of operation. This was also the case regarding the example design process discussed here.

From the broad range of tasks supported by the CNC controller developed in the project described here, only ‘programming of tool paths’ is selected as an illustration.

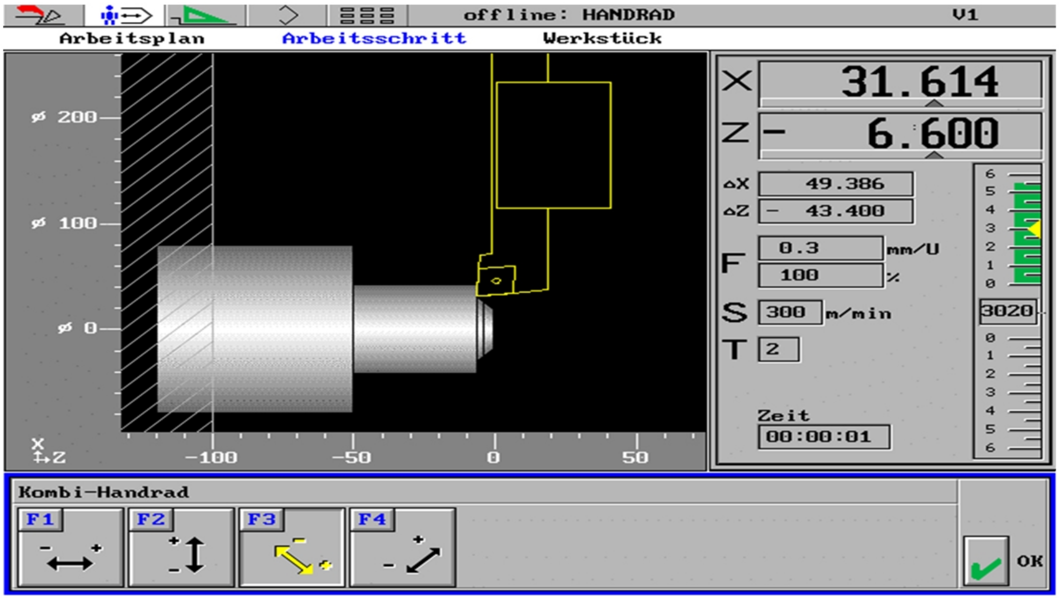


Figure 14: Direct manual processing with handwheel

The operation mode ‚Direct manual processing with handwheel‘ (figure 14) can be perceived as implementation of a kinetic model: The user controls the tool in a continuous movement with an electronic hand-wheel, in a similar way as he would do with a conventional lathe. From this input, the controller generates a program line (record-playback programming).

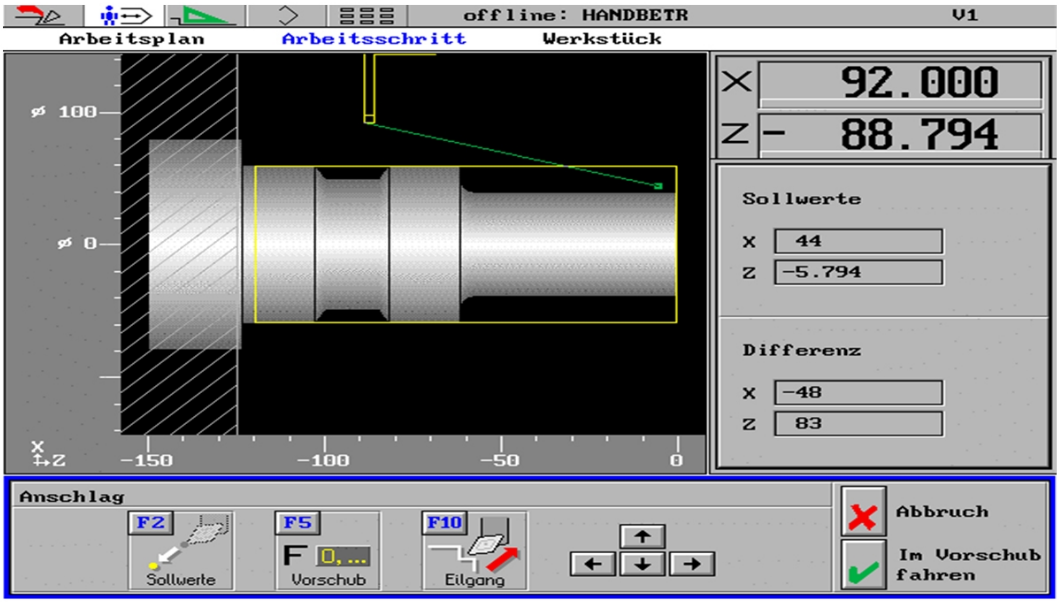


Figure 15: Positioning with handwheel

The operation mode ,,Positioning with handwheel‘ (figure 15) represents a sequential model: Using the electronic handwheel, the user controls – instead of the tool directly – a cursor, connected to the tip of the tool with a ‘rubber band’. A key command initiates a tool movement along the rubber band to and end point defined by the cursor position. The controller automatically generates a program line for this tool path.

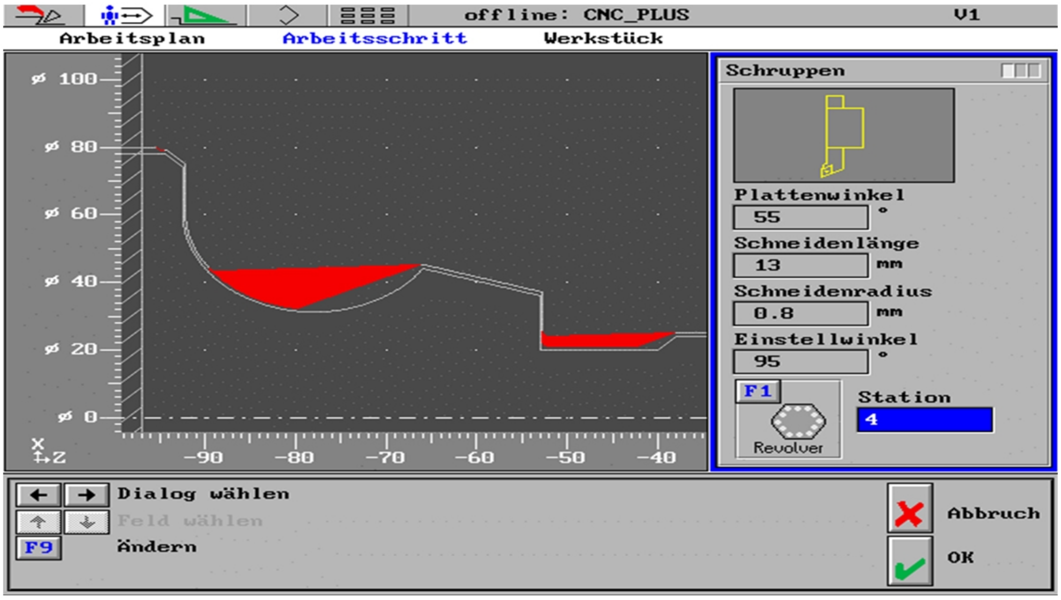


Figure 16: Automatic processing cycles

Finally, the mode of operation called ‘automatic processing cycles’ (figure 16) corresponds to a spatial model: The user describes the geometric contours of the raw part and the finished part, using graphic geometry menus. All tool paths are generated automatically and implicitly by the controller.

4 CONCLUSION

Today, ergonomics, ergonomic design, and the results of ergonomic design processes are widely recognised and appreciated in industry, regarding new and re-design of products for professional and private use as well as product presentation and sale. The ergonomic quality of products has become a major competitive advantage and sales proposition, although the actual product characteristics not always keep up with the promises articulated in product presentations.

When using ergonomic approaches in product design, some regulations and standards need to be kept in mind, as for example the European Machinery Directive (currently valid EC Machinery Directive 98/37/EC will be replaced from 29 December 2009 by the new Machinery Directive 2006/42/EC), or the German law regarding safety of devices and products (Geräte- und Produktsicherheitsgesetz, GPSG, issued January 2004). In Germany, all products to be used in commercial settings have to comply with the occupational safety law (Arbeitsschutzgesetz, ArbSchG, issued August 1996). This law requires companies to take into account up-to-date knowledge from the domains of occupational medicine and ergonomics.

Thus, ergonomic research results and design rules are not just recommendations without obligation. Rather, as a whole, they must be perceived as binding standards.

Besides engineering design and industrial design, ergonomics is a core domain within Integrated Product Design. One focal design objective in ergonomic product design is man-machine compatibility, regarding physical as well as psychological/mental/cognitive properties of humans. For both aspects – physical as well as psychological compatibility – approved design methods are available. Examples of these methods were described above.

Regarding engineering education, it is of paramount importance for engineering students to develop two aspects of competences during their participation in IDE programmes:

- Intradisciplinary competences: Knowledge and skills in the domain of ergonomic theory and methodology regarding physically and psychologically compatible man-machine interfaces.

- Interdisciplinary competences: Basic knowledge regarding neighbour disciplines like industrial design or work and organisational psychology, and skills regarding interdisciplinary cooperation with experts from the domains mentioned or other neighbour disciplines.

In the IPD programme at Otto-von-Guericke University, these requirements are met. For intradisciplinary competences, there are specific lectures and seminars in product ergonomics. For interdisciplinary competences, there are interdisciplinary design and development projects (IPD projects). In these projects, engineering students cooperate with students from these neighbour disciplines, to achieve best-possible solutions by combining their knowledge and skills.

The Institute for Ergonomics, Manufacturing Systems and Automation (IAF) at Otto-von-Guericke-University is responsible for basic and advanced education in ergonomics for engineering students, regarding product ergonomics as well as process ergonomics. Core objective of this educational programme is to make future engineers aware of ergonomic considerations, to prepare them for solving moderately complex ergonomic problems on their own, and to enable them for interdisciplinary cooperation regarding more demanding ergonomic challenges.

Close relations – in personal, organisational and content-related respects – between ergonomics and industrial design is a unique feature of the IAF and of Magdeburg engineering education. This unique feature will be perpetuated and further developed in the future.

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