Delphi Survey: Digital Ergonomics 2025

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Abstract

Research on how to support product and production design processes by computer-aided tools of ergonomics is one of the scientific focal points within the interdisciplinary field of ergonomics. Digital human models are an important aspect within this research context. Assuring a widespread use of these and other tools gives great potential for increasing product usability and designing safe, healthy and competitive work systems: The identification and redesign processes for dangerous or unhealthy product design and work system parameters can be moved into early product and production process design phases. In order to analyze specific future technological and organizational trends, an expert- and web-based, three-round Delphi survey on "Digital Ergonomics" was carried out from November 2011 until May 2012. A panel of 60 German experts was asked to answer nine lead questions in a first round. 26 statements were then built resulting from a qualitative data analysis of the received 886 answers. Each statement was evaluated according to its impact as well as its most probable date of occurrence in the second round. In the last round, the results of the second run were presented to the experts according to the Delphi technique and they were asked to assess the statements once again. During the whole Delphi survey the response rate was about 55%. Based on the results a ranking was built and the trends were sorted into seven categories according to their importance and most probable date of occurrence. Furthermore, named advantages, disadvantages and requirements of small and medium sized enterprises on digital human modeling were assessed. The results of the Delphi survey give an expert-based roadmap on trends in digital human modeling until 2025, which are presented in detail in this paper.

Keywords: Virtual ergonomics, digital human modeling, ergonomic product and process design, Delphi survey.

1. Introduction

Ergonomically designed socio-technical work systems and working equipment ensure safe, healthy and competitive work processes. Within this design context, computer-aided tools of ergonomics can significantly contribute: By virtually assessing the ergonomic fit of different design alternatives in an early product or process development stage, the amount of design errors causing unhealthy working conditions can be reduced significantly. Therefore, the quality of the planning results increases. It is of great interest to have detailed knowledge on upcoming trends within this domain of ergonomics.

2. Computer-aided tools of ergonomics

Computer-aided tools for human-centered product and process design are all based on knowledge and findings of the scientific discipline of ergonomics. A worldwide-accepted definition in this context is given by the International Ergonomics Association (IEA 2013):

> *"Ergonomics (or human factors) is the scientific discipline concerned with the understanding of the interactions among humans and other elements of a system, and the profession that applies theoretical principles, data and methods to design in order to optimize human well being and overall system performance."*

The definition of "Digital Ergonomics" worked out for this survey is based on the definitions of digital manufacturing (Zülch 2012), virtual production as well as ergonomics (ISO 6385; IEA 2013):

> *Digital ergonomics is a generic term enveloping computer-aided models and methods supporting the planning, the realization and the continuous improvement of products as well as social-technical work systems. The human being is considered as the main factor and integral part within this design perspective.*

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As a result, one main field of interest within this domain is digital human modeling (DHM) and according software systems as they fully comply with the given definition and therefore, support the virtual human-centered product and process design. DHM systems can be defined as

> *software systems that model features and abilities of the human organism or its elements and provide them for further simulation. By using these systems, simulation results within different scientific contexts such as ergonomics, cognition, medicine, biometrics and others can be generated" (Mühlstedt 2012, p. 26).*

A widespread use of these systems and other computer-aided tools of ergonomics form great potential for increasing usability of work equipment and designing safe, healthy and competitive work systems.
Therefore, the concept of "Digital Ergonomics" contributes significantly to preventive occupational safety and health due to its ability to identify hazardous work equipment or work processes already during the planning process. An example is the virtual 3D-evaluation of human-machine-interfaces with DHM systems.
Mühlstedt and Spanner-Ulmer (2009) presented survey results, giving a ranking of DHM system analysis features used amongst German ergonomists and furthermore, documented their interests for feature enhancements. The top three out of nine analysis features currently used are

- static visualization,
- analysis of reach and
- analysis of sight.

The top three out of nine analysis features unifying most interest in enhancements are

- analysis of posture,
- analysis of forces and moments and
- time studies.

Since specific manipulation functions are necessary for a context-sensitive utilization of analysis functions, the currently used features and their need of further development were analyzed as well (Mühlstedt and Spanner-Ulmer 2009). The top three out of nine manipulation features currently used are:

- manipulation of body posture,
- manipulation of hand posture and
- animation of the digital human model.

The top three out of nine manipulation features unifying most interest in enhancements are

- animation of the digital human model,
- manipulation of body posture,
- manipulation of hand posture.

The Delphi survey and its outcomes presented in this paper complement these mainly feature oriented results with upcoming DHM system application scenarios and resulting requirements for computer-aided tools of ergonomics. Within this context, the scope of application can be distinguished in general into two categories: product and manufacturing engineering according to the company divisions they are used in. Nevertheless, there are usually the same tools in place (e. g. DHM systems), only the used features differ. In product engineering, the application of computer-aided tools of ergonomics such as human simulation is mainly about the analysis of anticipated use and resulting man-machine-interactions. Within manufacturing engineering the design of the necessary work processes to produce the designed product are in focus. As a result, the experts were asked within the Delphi survey to distinguish their answers between product and manufacturing engineering if considered essential.

3. Delphi technique

The aim of the study "Digital Ergonomics 2025" was to identify upcoming technological as well as organizational trends in the domain of computer-aided tool of ergonomics and their importance. To achieve this goal, the Delphi technique, as basis for the survey design, was chosen. It is a commonly used approach within the scientific field of future research and technology foresight (Linstone and Turoff 1975).
The Delphi method was developed in the middle of the 20th century aiming at creating forecasts with maximal reliability. The goal of this approach is to generate and evaluate knowledge by an anonymous, group-communication based interaction of experts. The main goal is the reduction of uncertainty within the final prediction. To achieve this aim, a multi-round survey needs to be designed: in advance to each follow-up round the grouped intermediate results of the preliminary round are displayed as feedback to the experts. By doing so, each expert will evaluate under the influence of the previous judgments of the other experts (Dalkey and Helmer 1963; Häder 2009). It has been shown that usually after the second round the results change only to a small extent (Pandza 2008; Cuhls 2009). By assuring anonymity normative influences among the expert group are avoided (Cuhls 1998). An up-to-date approach to ensure survey efficiency and anonymity at the same time is a web-based survey.
Within the Delphi method four types can be distinguished (Häder 2009):

- Aggregation of ideas – qualitative aspects only (I);
- Aggregation and evaluation of ideas – high proportion of qualitative aspects, low proportion of quantitative aspects (II);
- Aggregation and evaluation of ideas – high proportion of qualitative and quantitative aspects (III);

- Evaluation of ideas – mostly quantitative aspects (IV);

The Delphi survey "Digital Ergonomics 2025" can be classified as type III because it had the objective to collect and evaluate ideas for the future development of computer-aided tools of ergonomics. To reach this goal the steps shown in figure 1 were followed sequentially. The survey was implemented with three web-based questionnaires assisting the collection of qualitative (ideas) and quantitative (evaluation) data.

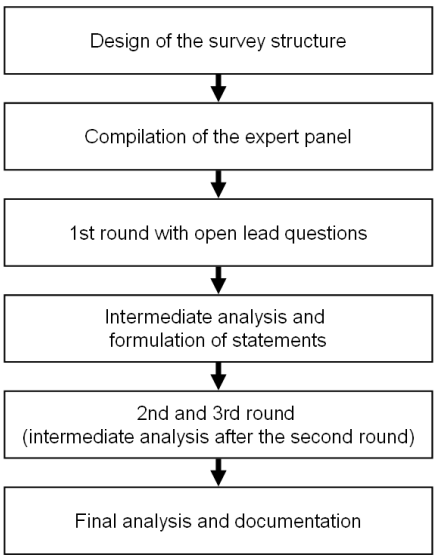

Figure 1: Delphi survey design procedure

Further information on the design of Delphi surveys and underlying scientific principles as well as a distinction from other approaches for technology forecasting can be found in Häder (2009) and Linstone and Turoff (1975).

4. Survey design

The Delphi survey was set up as a three-round web-based expert interview: at first, the experts had to answer (free text) nine lead questions. Based on these results, 26 statements referring to upcoming trends in "Digital Ergonomics" were abstracted. In the second round, the experts were asked to evaluate these statements according to their importance and most probable time of occurrence. Furthermore, they were asked to estimate the German competitiveness in "Digital Ergonomics" by 2025. The intermediate results were visualized and presented to the experts as feedback in the last third round as background knowledge when asked to assess the statements once again.
For each survey round a four week period time was chosen for the web-based data collection. When selecting the exact dates school holidays and intermediate data analyses periods were taken into account. The three survey rounds took place during the following periods:

- 1st survey round
  (Nov. 22, 2011 to Dec. 18, 2011)
- 2nd survey round
  (Feb. 20, 2012 to Mar. 18, 2012
- 3rd survey round
  (Apr. 16, 2012 to May 13, 2012)

Upon request, the experts had the chance to submit their answers offline assisted by an electronic document. In some cases answers were submitted outside but close to the survey round periods. In these cases, the submitted answers were considered in the analysis.

4.1. Putting together the expert panel

The starting point of the compilation of the German-speaking expert panel was a structured internet search. Furthermore, relevant experts were nominated by a project advisory group. The experts who agreed to participate were asked to nominate further individuals with high expertise. Following this approach a heterogeneous panel was put together with experts from scientific, industrial (software users as well as developers/vendors) and other institutions (see table 1). This ensured a wide consideration of opinions and interests.

Table 1: Composition of the expert panel

	#
Scientific community	18
Software users	24
Software vendors	12
Other institutions	6

4.2. Design of the 1st survey round questionnaire

At the beginning of each questionnaire, the experts were asked to give a short standardized self characterization (optional):

- affiliation,
- size of enterprise,
- self-assessment of expertise and
- professional experience.

The questionnaire consisted of nine lead questions with a political, economic, social or technical background. For each question up to five answers could be given (optional). The experts were asked to answer as generally as possible but at the same time as concretely as necessary. They were asked to distinguish their answers into small and medium enterprise (SME) respectively large scale enterprises (LSE) related issues (questions 4 to 8) and product or manufacturing engineering issues (questions 2 to 6 and 8) if necessary. The following questions were asked:

- Which social, economic and political influences do you expect to impose require-

ments relating to computer-aided tools of ergonomics?
- How will computer-aided tools of ergonomics evolve regarding their features and their analytical capacities?
- Which new technological developments do you expect regarding the use of and interaction with computer-aided tools of ergonomics?
- What are, from your point of view, the major advantages of computer-aided tools of ergonomics?
- What are the key barriers and deficits when using current computer-aided tools of ergonomics?
- Which company-related organizational changes concerning the product and manufacturing engineering do you expect to be caused by an increased use of computer-aided tools of ergonomics?
- What steps need to be taken to achieve a wide distribution of computer-aided tools of ergonomics to enhance ergonomic work system design until 2025?
- How do you rate the current situation regarding usage as well as research and development of computer-aided tools of ergonomics in Germany compared to other countries?
- Do you have any further remarks?

4.3. Design of the 2nd survey round questionnaire

Further to the optional self characterization part known from the 1st questionnaire, the experts were asked to evaluate 26 statements regarding their importance and their most probable date of occurrence. The statements were composed from the 886 1st round survey answers. The assessment of relevance was to be made on a seven-stepped scale shown in figure 2.

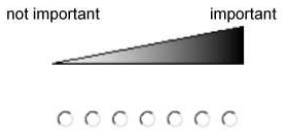

Figure 2: Evaluation scale for a statements importance

The assessment of the most probable date of occurrence had to be made according to the following scale:
- before 2015,
- between 2015 and 2020,
- between 2020 and 2025,
- post 2025,
- unlikely to happen.

The complete list of all 26 theses which have been generated based on the intermediate results of the first survey round and which were assessed by the experts in this second and the third survey round is presented in the results section.
Finally, the experts were asked to complete following statement about the competitiveness of Germany in "Digital Ergonomics": Germany is going to extent, keep or lose its co-leading role in the development and/ or usage of computer-aided tools of ergonomics compared to other nations by 2025 and beyond.
The evaluation of a statement regarding importance and most probable date of occurrence was required to get to the next statement and finally finish up the questionnaire.

4.4. Design of the 3rd survey round questionnaire

Further to the optional self characterization part known from the 1st and 2nd questionnaire, the experts were asked to evaluate the 26 statements regarding their importance and their most probable date of occurrence as well as the competitiveness question once again. The experts were given a results visualization of the second survey round outcome for each statement as feedback to support their reassessment (figure 3) as required by the Delphi technique.

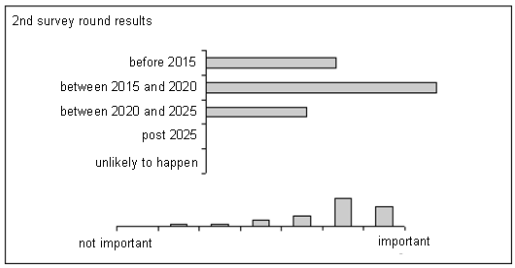

Figure 3: Results visualization given at the 3rd survey round questionnaire

As the last point, the experts were asked another question with the possibility of giving up to five answers (free text): Do you have any comments or recommendations regarding the future, distribution use as well as development of computer-aided tools of ergonomics especially for small and medium sized companies?

4.5. Technical implementation of the survey

The Delphi survey was implemented by means of the web-based survey platform "www.soscisurvey.de". The platform was selected due to the following features it provides:
- various question types,
- integration of images,
- access control allowing multi-round surveys with closed panels,
- free questionnaire layout design,
- free programming of filters,
- data exports to common spreadsheet applications or statistics software,
- SSL encrypted data transfer.

The data analysis was done based on the exported results from the survey portal using a spreadsheet application**.**

4.6. Intermediate 1st survey round results

35 partly complete data sets were analyzed after the first round. 886 answers could be taken into account for formulating upcoming trends in "Digital Ergonomics". Figure 4 shows the distribution of total as well as average answers per expert for each lead question.

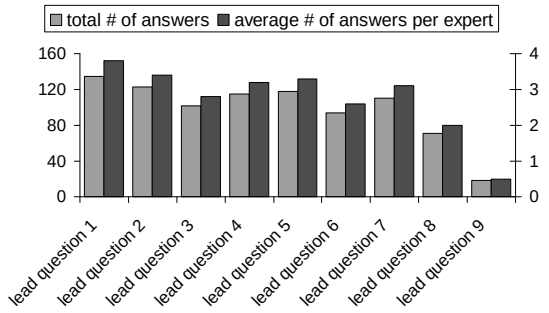

Figure 4: Total and average answers per expert (n=866)

The figure illustrates a nearly even distribution of answers to questions one to eight and an obvious lower number of responds to question nine. This last question asked the expert to give further comments if required. The results lead to the conclusion that the first eight lead questions adequately covered the research context. It can be assumed that the experts' answers provided an extensive view on future trends in "Digital Ergonomics".

4.7. Intermediate 2nd survey round results

32 complete data sets were analyzed after the 2nd survey round. The answers were then visualized as shown in figure 3 as input for the 3rd survey round. Since these outcomes solely describe intermediate results, they are not presented in this paper. A full list and a direct comparison of the 2nd and 3rd survey round results are documented in the full German survey report (Wischniewski 2013a).

5. Final survey results

The following section includes an expert's participation behavior and the results consisting of lists with advantages and challenges, upcoming trends as well as specific SME requirements in the context of "Digital Ergonomics".

5.1. Participation overview of the expert panel

In total 44 out of 60 asked experts participated in the Delphi survey. 40 provided personal data. Figure 5 shows the types of affiliation and the amount of associated experts.

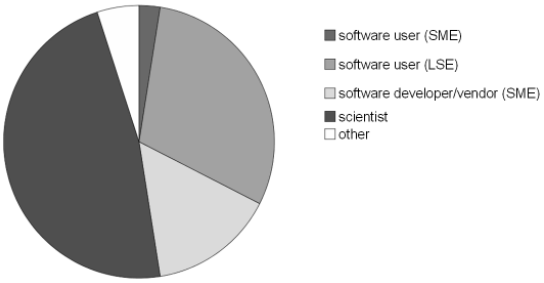

Figure 5: Affiliation types and associated experts (n=40)

A closer look at the participants list reveals on the one hand that software users, software developers / vendors and scientists took part in the Delphi survey. On the other hand, it attracts attention that software users are mostly affiliated to large scaled enterprises, while software developers are mostly affiliated to small and medium sized enterprises.
In addition to the affiliation statistics, figure 6 illustrates the expertise self-assessment, provided by the expert panel: 1 equals low expertise, 7 high. The box plot shows the median, the medial 50 percentile (bounded by upper and lower quartile) plus the extreme values of the given answers.

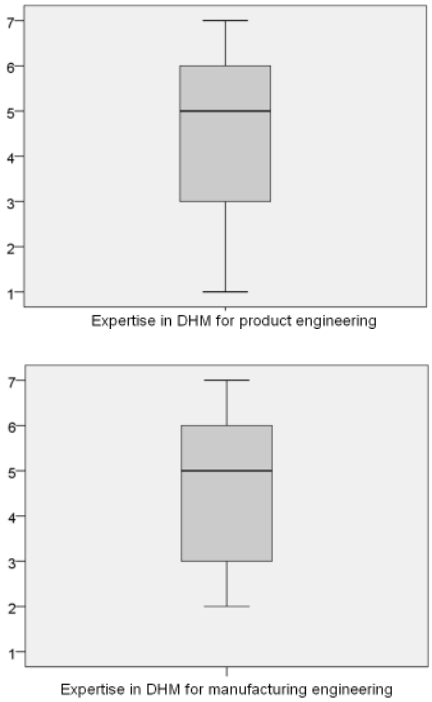

Figure 6: Self-assessment of expertise (n=40)

It is evident that the expert panel put together can rely on substantial knowledge in the field of "Digital Ergonomics". This is supported by professional experience in digital human modeling of the experts shown in figure 7.

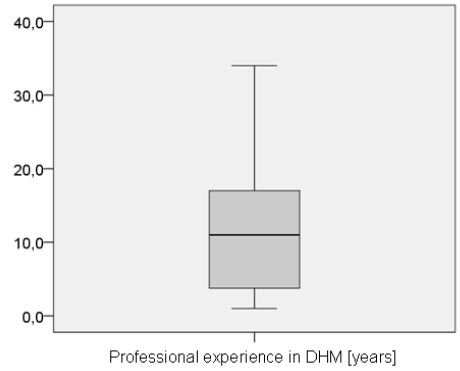

Figure 7: Professional experience in DHM (n=40)

In addition to the descriptive statistics of the expert panel, table 2 illustrates the specific participation of the experts in each round.

Table 2: Round-specific participation of the 44 experts

	#
all survey rounds	23
1st and 2nd survey round	2
1st and 3rd survey round	3
2nd and 3rd survey round	5
1st survey round only	7
2nd survey round only	2
3rd survey round only	2

5.2. Advantages of Digital Ergonomics

In the fourth lead question of the first survey round, the experts were asked to name advantages of current computer-aided tools of ergonomics. The results are based on 115 answers given. The listing is in descending order regarding quantity of identical expert indications. The use of computer-aided tools of ergonomics

- shortens development times (e. g. by reducing the number of hardware prototypes),
- enhances transparency along the product or manufacturing engineering process,
- provides ergonomic key performance indicators in an early design stage (e. g. through human simulation),
- allows an economical evaluation of different design alternatives,
- saves costs and
- improves visualization in the planning process.

Some isolated answers mentioned: the increase of subject safety by elimination of safety critical lab studies, the database capability of DHM systems and the linked easy generation of virtual surrogates of a target population.

5.3. Current challenges of Digital Ergonomics

In the fifth lead question of the first survey round, the experts were asked to name challenges or deficits of current computer-aided tools of ergonomics. The results are based on 118 answers given. The listing is in descending order regarding quantity of identical expert indications. Challenges and deficits using computer-aided tools of ergonomics result from

- high software complexity,
- in some cases unknown validity,
- a lack of standards for models and file formats,
- high investment costs,
- high efforts to build up virtual simulations and
- high operating costs.

Some isolated answers mentioned: challenges to integrate these tools into the company's existing software environment and lack of acceptance of computer-aided tools of ergonomics.

5.4. Upcoming trends in Digital Ergonomics

The 26 statements which describe upcoming trends in "Digital Ergonomics" are listed in seven categories according to their expert-evaluated importance and most probable date of occurrence.
A trend is classified important if the median expert-score from the 3rd survey round is greater than 4 (seven-stepped scale; see figure 2). Trends with a score of 4 are called "fuzzy" and everything below 4 is labeled as "not important". Accordingly, the median score of the last survey round is taken to identify the most probable date of occurrence. For this final analysis 31 complete and 2 partial data sets were considered.
The sequence of statements within each category is equivalent to the numeration in the questionnaire and provides no importance of ranking among them.

Important and state-of-the-art before 2015:

- Frequent exchange at national and international conferences and events fosters the transition of research results into practice.

Important and state-of-the-art between 2015 and 2020:

- Tools provide sufficient mapping of anthropometric and biomechanical variance (addressing the demographic change).
- Virtual ergonomic product and process validation is an important competitive asset.
- Generally accepted concepts for validation allow an accuracy classification of virtual ergonomic simulations.

- Software usability has increased significantly and supports software use ("ergonomic screenings") for novices.
- Motion capturing is a key element of ergonomic tools.
- Augmented and / or virtual reality is a key element of computer-aided tools of ergonomic.
- Accepted cost benefit analyses allow reasonable ROI calculations.
- Academic institutions provide relevant teaching. Trained experts are available and meet demands.
- By providing specific features in form of modules / apps companies can choose computer-aided tools of ergonomics according to their needs and budget.

Important and state-of-the-art 2020 and 2025

- Computer-aided tool of ergonomics can simulate cognitive processes in virtual and complex socio-technical work systems.
- Virtual ergonomic simulations have almost replaced real product and process evaluations.
- Products and processes are virtually designed and evaluated for different regions of the world supported by computer-aided tools of ergonomics.
- Standardized data formats enable a transfer of models and simulation results between different tools.
- The integration of virtual biomechanical models allows detailed and valid analyses of physical stress exceeding today's ergonomics screenings.
- Motion simulations are based on task instead of end point and / or trajectory definition; ergonomic assessments are done automatically.
- Visualization quality almost matches reality.
- Companies have standard organizational procedures to ensure ergonomic quality in product and process design that are used frequently.
- International standards for DHM are available and foster worldwide DHM system acceptance.

Fuzzy and state-of-the-art between 2020 and 2025:

- The software interfaces are multimodal (e. g. gesture recognition or data gloves).
- Many computer-aided tools of ergonomics can be used on mobile devices and are supported by cloud computing.

Important and state-of-the-art post 2025:

- Holistic tools allow the cognitive, anthropometric, biomechanical evaluation of products and work processes.

Important but probably never going to happen:

- Ergonomic issues are as important as costs, quality and time.
- Ergonomics is highly prioritized in companies and required resources (budget and personnel) are provided.

Not important and probably never going to happen:

- Laws and regulations are in place which require virtual ergonomic evaluations for safety reasons.
- Virtual ergonomic assessments get outsourced and are provided by service providers.

5.5. Requirement to increase spread among SMEs

Next to statement evaluation, the expert panel was asked to name specific requirements necessary to increase acceptance and usage of computer-aided tools of ergonomics among small and medium sized companies. 25 answers were analyzed. They were quite heterogeneous and often repeated named challenges from the first survey round. Therefore, the following list of answers represents mostly individual opinions:

- Improvement of software usability,
- Modularization / development of simple models to raise acceptance and usage,
- Reduction of investment and operational costs,
- Increase of know-how-transfer from LSE and research institutes to SMEs.

6. Conclusion

The presented results of the Delphi survey illustrate a roadmap with short-, middle- and long-term trends in "Digital Ergonomics".

In the web-based Delphi survey there were first 886 answers (free text) collected using nine lead questions regarding upcoming trends for computer-aided tools of ergonomics. Based on these answers 26 statements were abstracted and given to the experts in two additional survey rounds to evaluate importance and most probable date of occurrence. Furthermore, future competitiveness of Germany in the context of "Digital Ergonomics" was assessed and ideas to foster usage and distribution of computer-aided tools of ergonomics amongst SME were collected.

The statements were classified into seven categories according to their importance and the most probable date of occurrence. Most statements were evaluated "important" and "supposed to become reality"

between 2015 and 2020 (nine statements) or 2020 and 2025 (nine statements).
In addition to these two main lines the national and international networking (e. g. at conference events) was evaluated important and already happening.
The development of holistic DHM systems as well as the alignment of importance of ergonomics with today's key performance indicators (quality, cost and time) were rated "important" but visionary. Nevertheless, the experts estimate a continuous co-leading role of Germany in the context of "Digital Ergonomics".
The available few answers regarding the specific needs of SMEs can be summarized as follows:

- increase of software usability,
- modularization for a better matching of demand and budget,
- a better knowledge transfer from experienced LSE or scientific institutions to SMEs.

The current activities at the German Federal Institute for Occupational Safety and Health, which are an outcome of this survey, are for example the support of file and model standards development (Paul and Wischniewski 2012), the hosting of topic related events (BAuA 2013) as well as the analysis of anthropometric and biomechanical data sets (Wischniewski 2013b). The underlying objective of these initiatives is promoting the preventive design of safe, healthy and competitive labor.

References

BAuA, 2013. Trends und Strategien für den Einsatz digitaler Menschmodelle. In Proceedings of the Digital Ergonomics Symposium, 20 November 2012, Dortmund.
Cuhls K, 1998. Technikvorausschau in Japan: Ein Rückblick auf 30 Jahre Delphi. Physica Verlag, Heidelberg.
Cuhls K, 2009. Delphi-Befragungen in der Zukunftsforschung. In: Popp R, Schüll E. (Eds.): Zukunftsforschung und Zukunftsgestaltung. Beiträge aus Wissenschaft und Praxis. Springer Verlag, Berlin und Heidelberg, pp. 207-222.
Dalkey N.C, Helmer O, 1963. An experimental application of the Delphi method to the use of experts. Management Science, 9 (3), pp. 458-467.
Häder M, 2009. Delphi-Befragungen. VS Verlag für Sozialwissenschaften, Wiesbaden.
IEA, 2013.
http://iea.cc/01_what/What%20is%20Ergonomics.html, accessed April 30, 2013.
ISO 6385, 2004. Ergonomic principles in the design of work systems. Geneva, Switzerland.
Linstone H.A, Turoff M, 1975. The Delphi Method: Techniques and Applications. Addison-Wesley Educational Publishers, Boston, Massachusetts.
Mühlstedt J, 2012. Entwicklung eines Modells dynamisch-muskulärer Arbeitsbeanspruchungen auf Basis digitaler Menschmodelle. Dissertation, TU Chemnitz.
Mühlstedt J, Spanner-Ulmer B, 2009. Homo Sapiens Digitalis: Über den Praxiseinsatz digitaler Menschmodelle. In: Lichtenstein A, Stößel C, Clemens C. (Eds.), 8. Berliner Werkstatt Mensch-Maschine-Systeme. VDI Verlag, Düsseldorf.
Pandza K, 2008. Delphi Method. In: Thorpe R, Holt R, (Eds.), The SAGE Dictionary of QUALITATIVA MANAGEMENT RESEARCH, SAGE Publications Ltd, London, pp. 73-74.
Paul G, Wischniewski S, 2012. Standardization of Digital Human Models. Ergonomics, Vol. 55, N° 9, pp. 1115-1118.
Wischniewski S, 2013a. Delphi-Studie Digitale Ergonomie 2025, BAuA, Dortmund, 2013.
Wischniewski S, 2013b. Bivariate Parametrierung digitaler Menschmodelle mittels Körperhöhe und Körpergewicht. In: Proceedings of 59. Arbeitswissenschaftlichen Kongress der Gesellschaft für Arbeitswissenschaft, February 27 – March 1 2013, Hochschule Niederrhein, Krefeld, pp. 363-366.
Zülch, G, 2012. Features and limitations of digital human models – a new German guideline. A Journal of Prevention, Assessment and Rehabilitation, 41 (Suppl 1), pp. 2253–2259.