Ergonomic assessment of automotive assembly tasks with digital human modelling and the 'ergonomics assessment worksheet' (EAWS)

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Abstract: The increasing global competition and changing demographic profiles amplify the importance of efficient design of work stations and processes that considers the physical job demands and the operators' abilities. Good ergonomic design is not restricted to the current production, but should be considered during all phases of the product life cycle. Digital human model (DHM) simulations provide good opportunities for an integrated ergonomic design, particularly during pre-production planning. This article gives an overview on DHM used in production ergonomics and highlights two new approaches to enhance current DHM applications. The editor for manual work activities (EMA) helps to speed up and optimise human movement simulation. MTMergonomics is an ergonomic risk assessment tool for industrial engineers (and ergonomists) during the planning phase of the product development process, based on MTM process languages like MTM-UAS. The ergonomic assessment worksheet (EAWS) is a tool for the holistic evaluation of physical workloads. It is implemented in digital human models like Jack and serves as an ergonomic evaluation tool within EMA and MTMergonomics. EAWS serves as a common feature to link DHM, EMA and MTMergonomics activities.

Keywords: anthropometry; biomechanics; physiology; risk assessment; editor for manual work activities; EMA; ergonomics assessment worksheet; EAWS; MTMergonomics; EU legal requirements; physical workload; digital human model; DHM.

Reference to this paper should be made as follows: Schaub, K.G., Mühlstedt, J., Illmann, B., Bauer, S., Fritzsche, L., Wagner, T., Bullinger-Hoffmann, A.C. and Bruder, R. (2012) 'Ergonomic assessment of automotive assembly tasks with digital human modelling and the 'ergonomics assessment worksheet' (EAWS)', *Int. J. Human Factors Modelling and Simulation*, Vol. 3, Nos. 3/4, pp.398–426.

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1 Introduction

An increasing global competition and changing demographic profiles in industrialised countries stress the importance of designing work stations and processes in a lean way. This is especially due to the fact that in industrialised nations musculoskeletal disorders (MSD) cause almost one third of all cases of sick leave (European Agency for Safety and Health at Work: Zinta Podniece, 2008). Good ergonomic design that considers the job demands and the operators' characteristics and abilities may help to reduce physical workload and optimise the production workflow (Bierwirth et al., 2012b). However, it is important to acknowledge that ergonomic design is not restricted to improving the current production, but should be considered during all phases of the product life cycle: the earlier ergonomic concerns are detected, the earlier they can be resolved (Schaub et al., 2012a, 2012b). Digital human model (DHM) simulations provide a high potential for preventive ergonomic work design, particularly during pre-production planning (Duffy, 2009).

Human modelling started almost 40 years ago. The first university development was system for aiding man machine interaction evaluation (SAMMIE) at the University of Nottingham (UK) (Bonney and Case, 1976). The first industrial applications started in aviation industries with BOEMAN (Ryan, 1971) and in automotive industries with CYBERMAN (Blakely, 1980). In addition to anthropometric models, but biomechanical man models (*Combiman*, Kroemer, 1973) were also implemented in this early modelling phase. The number of new DHMs grew rapidly in the following years and some of them still exist. An overview on those 'early' man models can be found in Schaub (1988).

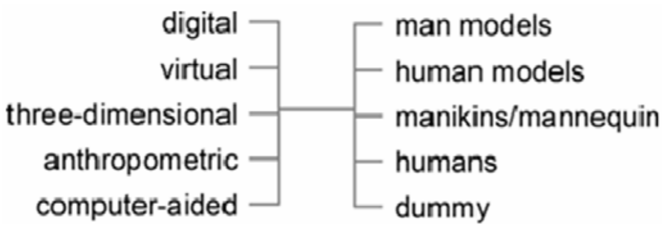
This article gives an overview on DHM used in production ergonomics and introduces three new approaches to enhance current DHM applications. The first is editor for manual work activities (EMA) that helps to speed up and optimise human movement simulation. The second is MTMergonomics that links DHM to high quality descriptions of the work tasks using standardised process languages (e.g., MTM-1, MTM-UAS). The ergonomics assessment worksheet (EAWS) finally is a tool for the holistic evaluation of physical workloads. It can be used throughout the whole product lifecycle, which also includes the application of DHM during the phase of the digital factory (Schaub et al., 2008a, 2008b). As EAWS is implemented in DHMs like Jack (Mühlstedt, 2012) and planning tools like EMA and MTMergonomics (Schaub et al., 2009a) EAWS serves as a link between DHM, EMA, and MTMergonomics for the evaluation of physical workload.

2 Background

2.1 DHMs in automotive production

DHMs represent the human being in a software system or a part of a software system. They embody the complete or partial human characteristics and abilities. By using these systems in specific scenarios in the field of ergonomics, cognitions, medical science, biometrics and others, insights can be derived. For these subject areas, the technical term DHM has become established. Furthermore, other terms can be found in publications and linguistic usage (Figure 1). DHMs are used in product ergonomics for designing the interior, the position of the driver and of controls. Beside this, the models are used for manufacturing design, for example to define work places, acceptable stress or the work environment.

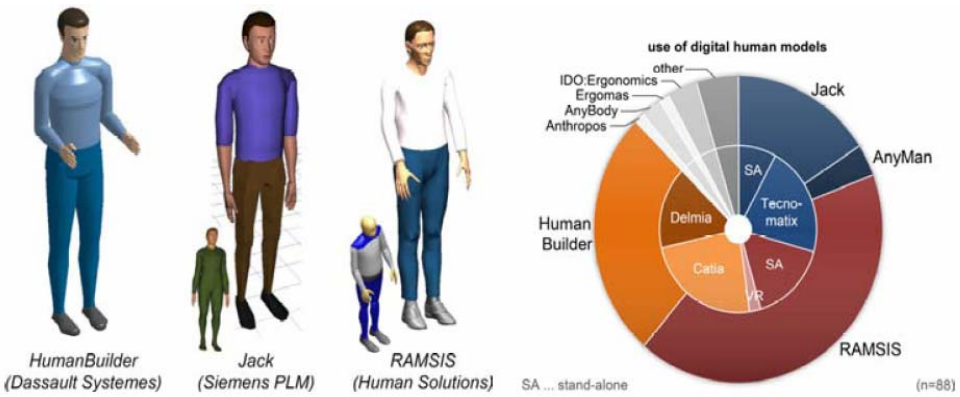
Figure 1 Different terms used for DHMs in various sources of English literature



2.1.1 DHMs in production ergonomics

DHMs, such as Human Builder, Jack and Realistic Anthropological Mathematical System for Interior Comfort Simulation (RAMSIS), can be used for ergonomic studies and are, when integrated in a computer-aided design (CAD) system, a helpful tool for designers during the product development process (PDP) as well as the planning process in digital factories (Figure 2). They enable the use of anthropometric data, reproduction of body postures and investigation of ergonomic issues in design and manufacturing.

Figure 2 Important ergonomic DHMs and their usage (see online version for colours)



Source: Taken from a survey in Germany (Mühlstedt and Spanner-Ulmer, 2009).

Catalogues of DHMs are described in Seidl's (1994) doctoral thesis, in contributions from Bubb and Fritzsche (2008), LaFiandra (2009) and Li (2008) in *Handbook of Digital Human Modeling* from Duffy (2008) as well as in the doctoral thesis from Mühlstedt (2012). A survey from 2009 among German practitioners, Mühlstedt (2012) identified the three most popular and currently used DHMs Human Builder, Jack and RAMSIS (Figure 2). In the following, their specific characteristics and functions for production ergonomics will be introduced.

2.1.1.1 Human Builder

Human Builder (Figure 2) is a part of the CAD-application DELMIA by Dassault Systemes that provides a set of tools to examine products and processes. It is also available in CATIA V5. The model refers to data from various populations (France, America, Canada, Japan, Korea) excluding growth acceleration. When the model is positioned via forward kinematics, inverse kinematics or predefined postures, it considers natural limitations of the joint angle. Additional to the basic functions extra packages are available for ergonomic analysis. The add-on human activity analysis can be used to investigate static body postures using rapid upper limb assessment (RULA) (McAtamney and Corlett, 1993), lifting and carrying using the NIOSH (Waters et al., 1993) equations and pushing/pulling using the Snook and Ciriello (1991) tables. Human posture analysis enables qualitative and quantitative posture analyses with individual values for each joint by means of comfort and discomfort areas defined by the user. An automatic posture optimisation completes these features. Human task simulation allows motion simulations for work processes to investigate ergonomic and occupational safety aspects. Climbing stairs, using a ladder, creation of macro-like motion paths as well as key frame animation are provided (Kühn, 2006; Green and Hudson, 2010; Fireman and Lesinski, 2009).

2.1.1.2 Jack

In the mid-‘80s of the last century Jack (Figure 2) was introduced by the University of Pennsylvania (Center for Human Modeling) in cooperation with NASA and the company Transom Technologies Inc. Under the name Classic Jack, also Jack stand-alone, the human model is available as an individual software; likewise it is linked to the product lifecycle management (PLM) suite Tecnomatix, the CAD-system NX (NX Human) and the software Teamcenter (VIS Jack). Tecnomatix was developed for application in the digital factory. Work sequences and procedures, the workplace, cycle times and ergonomic conditions can be analysed. Movement macros, such as gripping objects, enable an efficient use. The basic data for the human model Jack is provided by the anthropometric database Ansur. The flexible spine and joints allow versatile applications. A number of analysis functions are integrated into the system (strength analysis, lifting, carrying, risk analysis, etc.). There are other complementary packages for Jack. These include task analysis toolkit for ergonomic work place design and motion capture toolkit for record of real movement data. Possible analyses with Tecnomatix are cycle time and ergonomic assessments (lifting, body posture, energy use), reachability analyses, time analyses according to MTM, visibility evaluations, interference analyses, lifting/carrying referring to NIOSH and analyses of hand-arm-movements (Reed, 2009; Kühn, 2006; Siemens PLM, 2012).

2.1.1.3 Realistic Anthropological Mathematical System for Interior Comfort Simulation

The human model known as the acronym RAMSIS (Figure 2) was originally developed at the Institute of Ergonomics (TU München), Katholische Universität Eichstätt and a research association of automotive manufacturers. RAMSIS is mainly used for product design. Especially adapted to the needs of the automotive industry, it can be used as a single application or as an integrated application in the CAD system CATIA. It is also available as a production-oriented implementation in the PLM software Tecnomatix.

The main applications of RAMSIS are ergonomic studies in cockpits of vehicles, aircrafts and construction machineries. The system integrates many sophisticated databases with several populations of different ages, differentiation according to percentiles, somatotypes and includes growth acceleration (Bubb and Fritzsche, 2009; Lämkull et al., 2009; Seidl, 1994).

In addition to the human models described above, which have the largest distribution in practice, there are others that are also classified as ergonomic DHMs. Their distribution among practitioners is less significant or their range of functions is limited. 'Anyman' is similar to Jack as the former part of the Tecnomatix-System. Even in the CAD system CREO, formerly known as PRO/Engineer Wildfire the human model called manikin is available. The human model implemented in DELMIA Process Engineer (DPE) is used for work place analyses with particular focus on economic time management issues. A fairly new, but increasingly important DHM, is the EMA by IMK automotive which integrates production ergonomics and process planning based on MTM standard times (see Section 2.2).

2.1.1.4 Characteristics of DHMs for production ergonomics

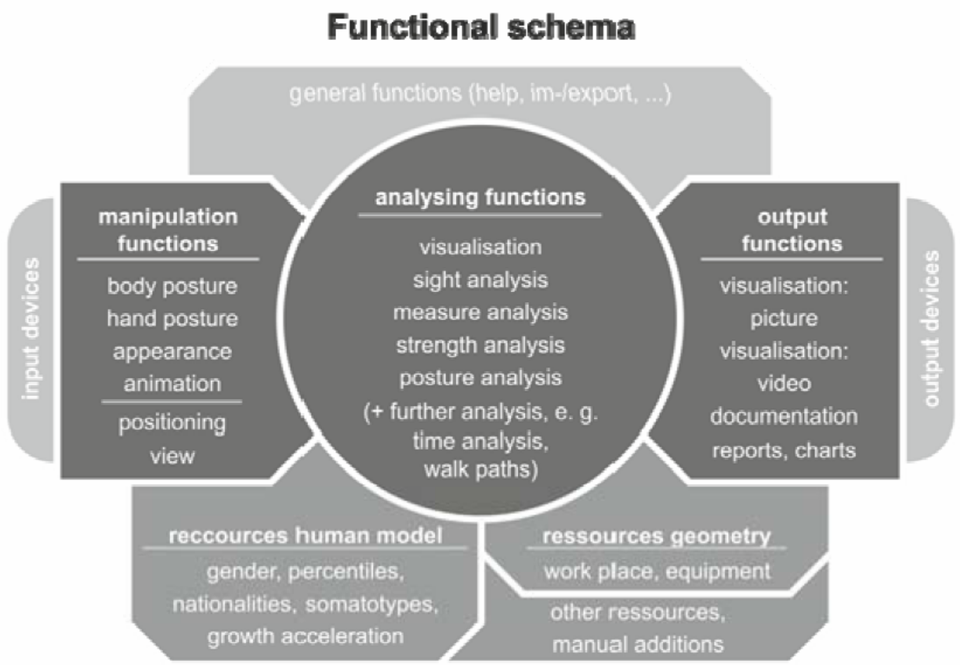
Ergonomic DHMs have many common characteristics and functions. The models are based on an abstract skeleton model, which couples segments (bones) with joints. The joints have zero to three rotational degrees of freedom which enables the reproduction of body postures. Furthermore, DHMs for production ergonomics have a surface to represent skin or clothes. In many systems, a three-dimensional body is coupled to a segment and accordingly moves in the same way. This results in unrealistic representations at the transition or interfaces of the three-dimensional objects, especially in extreme positions of the joints. Consequently, newer systems include surfaces with deformable skin and clothing (polygonal mesh with textures). The models can be positioned with forward kinematics, inverse kinematics or via access to a posture database. Either the human model has sufficient im-/export-interfaces or it is implemented as a plug-in or part of a PLM software. Therefore, direct access to the data provided by designers and planners is possible.

2.1.2 Functional schema of DHMs

During an ergonomic analysis with DHMs – that means the actual use of software tools – many functions are used. Figure 3 illustrates a collection of functions and methods provided by DHM.

Following the functional schema (Mühlstedt, 2012; Green, 2000; Lämkull et al., 2009), a typical workflow for the use of DHMs can be retraced. Based on an analysis the human model will be created using anthropometric resources of the system. Furthermore, three-dimensional geometries for the environment and necessary resources are created or imported respectively made available within the CAD or PLM system. Using the input and output devices most important functions of the system can be used. By means of manipulation functions body postures of the human model and other characteristics (e.g., appearance) can be determined. Three essential functions are used to adjust the body posture: forward kinematics, inverse kinematics and posture databases. In addition to the body posture manipulation the positioning functions of the human model in three-dimensional space and the continuous use of view-changing tools are essential. Subsequently, various analyses can be performed using basic ergonomic methods. The current, inherent to the system, visualisation is the basic and most important function. In addition, by means of a sight analysis, the viewing zone can be determined. Analyses supported by the use of reach envelopes investigate, for instance the reachability of control levers; measurement analyses examine distances and movement space, whereas force or posture analyses assess body posture. Other functions for load handling and energy consumption lead to additional insights. Functionality and the number of ergonomic methods vary from system to system. The result of ergonomics methods visualise the output functions and are presented in a further processable form. In addition, the use of the systems general functions, such as help or im-/export functions can be used.

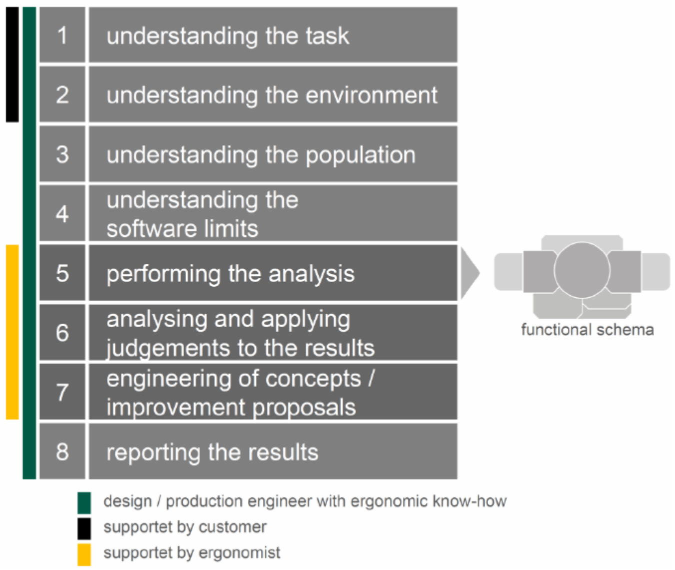
Figure 3 Functional schema of DHMs including elements for an ergonomic analysis



2.1.3 Advanced analysis methodology for virtual production ergonomics

In order to use DHMs in a methodologically meaningful way, it is very helpful to proceed according to a standardised methodology. 'A generic process model for human analysis' was presented by Green (2000). Lämkull et al. (2009) compared the steps to various working persons. Mühlstedt (2012) extended the methodology with a further step in developing drafts and proposals for improvement.

Figure 4 Steps during the performance of an ergonomic study with DHMs (modified from Green, 2000) and persons involved (modified from Lämkull et al., 2009) (see online version for colours)



The first step is to understand the task, i.e., the requirements of the assigned task. It includes the elements of the work system or functional elements of the design, required tools and utilities, the human-machine interface and the necessary body postures and forces. In addition, controls, displays, time or space limitations and repetitive tasks need to be analysed. Closely connected with the first step is to understand the environment of the workplace or product. These include the fixed and moving objects, which interact, as well as any possible hazards and work environment conditions. During the first two steps a close communication with the client is useful in order to find requirements in detail.

These design methodologies, which can also be found in other basic considerations, are followed by two further analysis steps, which can be assigned to virtual ergonomics specifically. On the one hand, to understand the population investigates the persons confronted with the product or work place. This includes the actually interacting people and the people in the area, each with their anthropometric variables and other relevant characteristics. In addition, advices concerning special requirements for protective, e.g., clothing, helmets, glasses, shoes or other objects need to be worn. On the other hand potential limitations of the software system are discussed in addition to the computer-assisted methods or techniques. This concerns the limits of the primary software system used and the consequent need for additional pen-and-paper ergonomic methods. Afterwards, the real work is done with the system of virtual ergonomics with the implemented ergonomic analysis. A subsequent analysis and judgement of the results of the analysis can be done with an adjustment to the requirements. At this point it becomes apparent which requirements can be met, such as functions and mechanisms of action of the product or elements of the workplace should be designed. Prioritisation of the elements helps to specify the solution. In both of these support of an ergonomist is reasonable.

Finally, the engineering of concepts and improvement proposals can support the goal of better designed products or ergonomic workplaces. All elements of the design solution need to be considered within the desired level of detail in a conscientious way. A final documentation of the study summarises important background information, such as anthropometric data sources, body measurements, results of analysis, solution drafts, proposals of improvement and relevant contact persons. Thus, a full traceability is ensured.

2.2 Enhancing efficiency and accuracy of DHMs with EMA

The newly developed software tool 'EMA' was created by the German engineering consulting company *IMK Automotive* in cooperation with Chemnitz University of Technology. EMA utilises a modular approach for planning and simulating manual human labour in industrial settings. These modules are based on so called 'complex operations' representing an aggregation of single elementary movements that are directed at carrying out a certain work task. Thereby, EMA strongly reduces the effort for simulating human work because it enables production planners to generate a simulation of the entire work process by describing operations in a natural planning language like 'get and place part' or 'use hand tool'. In contrast, other DHM tools demand the production planners to rather animate the DHM by teaching each single body movement that is needed to perform the work.

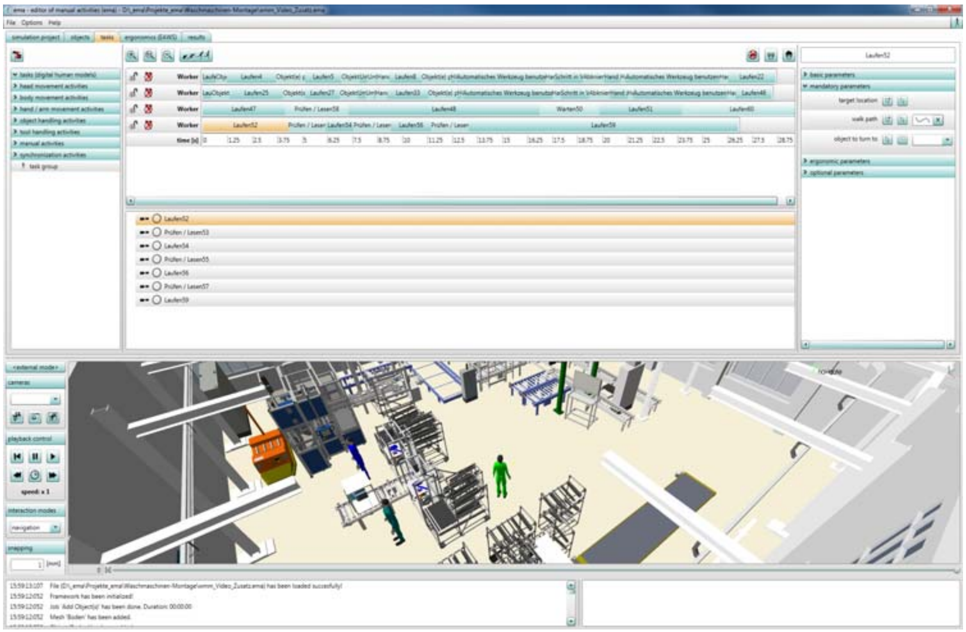
2.2.1 Defining complex operations

EMA utilises a modular approach for simulating human work activities that is based on 'complex operations'. Complex operations represent an aggregation of elementary movements that are commonly directed at carrying out one work task in a logical sequence. For instance, the operation 'get and place part' may consist of the following elementary movements: steps forward – bend – hand to object – pick object – object to body – step backward – turn – steps forward – bend – hand to target – place object – let loose – hand back. In contrast to other human modelling software, EMA automatically calculates all elementary movements that are necessary to perform the operation so that the planning engineer must not teach every single movement. In the example above, the planner only defines what part needs to be placed in which location, while EMA calculates all body movements including walkways.

Of course, many complex operations are needed for simulating human work in industrial settings. Thus, EMA is constantly being improved by adding more complicated and more specific operations, for example car ingress and egress. Figure 5 shows a list of all complex operations that are currently available in EMA.

In order to achieve correct simulation results, the calculation of EMA movements is based on highly automated algorithms that were derived from theoretical analyses and validated in motion-capturing studies as well as in practice. In the first step, relevant operations and their elementary movements were defined based on theoretical analyses and practical observations. Secondly, operations were simulated using available DHM tools such as Delmia V5 teaching the human manikin all elementary movements step-by-step. Thirdly, these basic modules were refined using motion capturing data recorded with experienced industrial operators. Typical movement trajectories and relevant parameters were derived by comparing the movements of different operators performing standardised tasks in varying conditions (e.g., different working heights). As a result, EMA developers defined a set of algorithms that consist of movement influencing parameters and describe an average or prototypical movement under the given conditions.

Figure 5 EMA user interface (stand-alone version) (see online version for colours)



These algorithms were built and optimised for all relevant complex operations. However, the most difficult task was the software-technical implementation. Therefore, a number of parameters were defined for each complex operation enabling the software user to quickly adjust the boundary conditions of the work task, for instance the weight of the part. Large efforts of testing were invested to optimise these algorithms for each operational step in accordance with biomechanical and ergonomic principles. Moreover, many practical examples from automotive and other engineering industries were simulated with EMA and analysed with practitioners to evaluate plausibility and correctness of movements. These are ongoing activities so that EMA is constantly being improved based on the feedback of EMA software users in practice.

2.2.2 EMA software tool

EMA is conceptualised as an open software system. The simulation kernel can be incorporated in any available PLM system and any 3D-engine due to its modular architecture and various interfaces. However, there is also a stand-alone version that aims to support small and medium-size companies who may not be able to afford large PLM systems.

In the current version, EMA is available as plug-in for DELMIA V5, which is one of the leading PLM-systems for automotive production planning. As mentioned above, DELMIA already provides a 3D man-model (Human Builder) that, however, can only generate dynamic human simulations by defining single body movements in a very time-consuming step-by-step process. Such so called ‘MoveToPosture’ activities contain information about the current values for joint angles and the necessary time for reaching a certain target posture. Incorporating EMA into DELMIA aims at reducing the time effort, handling difficulties, and inaccuracies of the current modelling process. The following section briefly describes the EMA application as DELMIA plug-in, the so called EMA-V5. The workflow with the EMA stand-alone version with integrated graphic engine is similar, but even more time-efficient. Figure 6 illustrates the user interface of the standalone version with its 3D simulation environment and the interface for creating sequential and parallel activities. The illustrated work system is part of a short-cycled washing machine assembly line including logistic areas and multiple workers.

Figure 6 EMA user interface for ergonomic assessment (see online version for colours)

Before starting to work with the EMA-V5, the production planner first needs to prepare the simulation environment with regular DELMIA tools. To this end, all relevant data of products (e.g., parts) and resources (e.g., machinery) have to be loaded and saved in their ‘initial state’. Furthermore, at least one human model needs to be added to the scene; all properties of the human model (e.g., height, gender) may be defined in the DELMIA ‘Human Builder’. Following that, the planner may start the EMA-V5 plug-in that is part of the workbench ‘human task simulation’. In the next step, the pre-defined complex operations that are categorised and presented on the left side of the screen may be used for describing the work process with a simple drag-and-drop mechanism that is adding operations to the human model task bar. EMA-V5 automatically presents parameters to specify the operation after it is added to the task bar – in some cases specifications have to be completed with drop-down menus (e.g., object to pick-up), whereas other parameters are defined by directly interacting with the 3D simulation environment via mouse click (e.g., point of assembly). Based on the parameter settings all pre-defined movements that are included in the complex operation are adapted and calculated to fit the specific situation. This approach enables the planner to describe the entire work process only by choosing the correct operations and entering a small number of defining parameters instead of simulating each particular posture step-by-step.

Following the interactive description of the work process EMA-V5 automatically generates the 3D human simulation including all single steps (MoveToPostures) that are stored into the DELMIA process structure. Furthermore, by running the simulation EMA-V5 automatically calculates the MTM-time for each operation and the entire work process. The MTM analyses can be stored and, potentially, directly transferred to alphanumerical planning software, such as DPE.

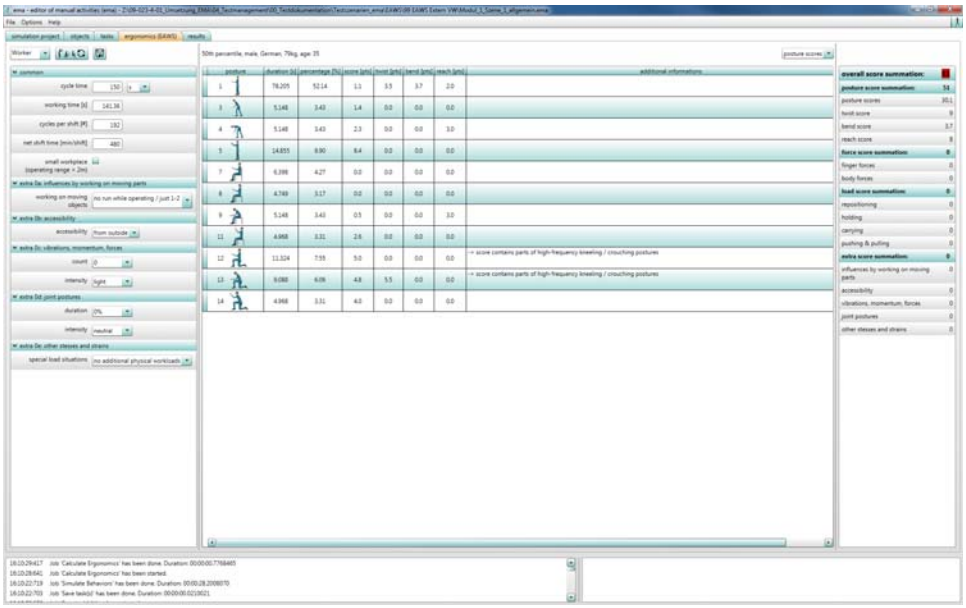
2.2.3 Ergonomic risk assessment with EMA

From their early beginning, DHMs were mainly used for analysing anthropometrics and optimising ergonomics in industrial work settings. Early models were focusing static investigations of reachability and buildability. EMA now allows investigating ergonomic conditions of the entire work process including dynamic aspects of body posture and forces. More precise ergonomic evaluations across a certain period of time are possible because biomechanical correctness and a high accuracy of movements were both important criteria for defining the complex operation modules in EMA.

EMA has therefore included a standard tool for ergonomic risk assessment called EAWS (see Section 3.4), which focuses of process evaluation rather than static ergonomic investigations. Previous research shows that this paper-pencil checklist produces reliable results in real-world applications as well as in the ergonomic assessment of human work simulations (Fritzsche, 2010). In contrast to other methods like RULA (McAtamney and Corlett, 1993) or OWAS (Karhu et al., 1981), which are both mainly focused on the evaluation of postures, EAWS includes several physical risk factors including action forces, weight handling and extra strains. Moreover, EAWS provides a holistic evaluation of the entire work process taking the intensity, duration, and frequency of risk factors into account. Based on the EAWS risk assessment, EMA enables a semiautomatic ergonomic evaluation by analysing the recorded joint angles and positions of the body segments throughout the entire simulation. Based on this data each posture is categorised into one of the standard posture classes defined by EAWS (e.g., standing upright, bend forward, overhead). Figure 7 shows a summary of those postures as part of the ergonomic assessment. This approach not only improves the efficiency but also the objectivity of posture evaluations with human simulations.

To complete ergonomic evaluation, information regarding action forces and objects weights need to be added by the user. Finally, EMA combines all ergonomic data and calculates a total risk score that is rated into three risk categories (green, yellow, red). The calculation of the risk score and the risk rating follow exactly the rules of the EAWS paper-pencil-method (see Section 3.4). EMA therefore allows a comprehensive semi-automatic ergonomic assessment by using automatically retrieved data on postures that are combined with data on forces and weights provided by the user.

Figure 7 EMA user interface for ergonomic assessment, postures and risk scores are calculated based on the EAWS method (see online version for colours)



2.3 *Ergonomic risk assessments using EAWS*

Whenever carrying out ergonomic risk assessments there should be a clear indication whether the assessed risk is at a tolerable level or if an ergonomic intervention is required. The EAWS (Schaub et al., 2010, 2012a) considers physical workload only and evaluates it on a three zone (traffic light scheme) rating system as described below. EAWS focuses especially on existing CEN and ISO standards, which consider physical workload in terms of working postures, action forces, manual materials handling and repetitive loads of the upper limbs. For each of those four types of physical workload one of the standards will offer a risk assessment. This is of limited value for practical applications, as real tasks in industry do not contain either ‘working postures’ or ‘manual materials handling’, but might be a combination of all four types. Considering standards the question arises, if a ‘yellow’ ‘working posture’ and a ‘yellow’ ‘manual materials handling’ will produce a total ‘yellow’ assessment, or if they might compensate to a ‘green’ or aggregate to a ‘red’ total. Solving this question was the primary purpose for the development of tools like EAWS. The acceptance of those tools in industry is an indicator for the needs based on real working tasks (see Table 1). Due to the dual European system of ‘health and safety at work’, ergonomic risk analysis is not only needed during the production phase, but also during the design phase. This involves the need to integrate the EAWS or similar risk assessment tools into software tools that are used during the design phases of a PDP (Schaub et al., 2009a; Toledo, 2012; Walther and Toledo, 2012; Neubert et al., 2012).

Table 1 Dissemination of ergonomics risk assessment tools of the EAWS family in European industries

Company	*Tool name*	*Origin*	*Date of implementation*
Opel/GME	NPW	div.	Implemented 1997
Porsche	DesignCheck	div.	Implemented 1997
Daimler	EAB, EAB neu, ESC, ECL and BELAS	SAK, EAWS and IAD-BkB	Developed by Daimler/IAD, implementation in 2000, 2005 and in progress
Bosch	IAD-BkB, 'Bosch' and div., EAWS	IAD-BkB, EAWS and div.	Implementation in progress, implemented 2005
Audi	APSA neu	Based on AAWS, IAD-BkB	Developed by Audi, Implemented 2006
Karman	AAWS	AAWS	Implemented 2007
Smart	S-Erg	EAWS	Implemented 2007
DAF	AAWS	AAWS	Development and implementation in progress
Fiat group	EAWS	EAWS	Implementation in progress
Volkswagen group	EAWS/AAWS	EAWS, AAWS	Implementation in progress
Var. Big and SMEs in BW	IAD-BkB	AAWS/EAWS	Implementation since 2005

2.3.1 History

In the '90s of the last century the development of ergonomic screening tools for physical workload showed first results (Schaub, 1993a, 1993b, 2002). In 1997, the development of screening tools for automotive industries lead to the 'new production worksheet' (NPW) (Schaub and Dietz, 2000), which was initiated by General Motors Europe (GME) and realised in cooperation with Adam Opel AG. Developed and tested at 258 work stations at Ruesselsheim plant the NPW is currently used in all German and other GME plants (Schaub and Kaltbeitzel, 2006).

Later on the automotive assembly worksheet (AAWS) was developed and checked for validation and applicability (Schaub et al., 2008a, 2008b). The AAWS is based on the NPW (Schaub and Storz, 2003; Landau et al., 2008) and DesignCheck (Schaub et al., 1999, 2000; Winter et al., 2006).

Later on, the AAWS was enriched by a section for the evaluation of upper limbs, which is of major concern for electrical industries and automotive suppliers. Revising the AAWS for the increased field of application generated the new European assembly worksheet (Schaub and Ghezel-Ahmadi, 2007; Schaub et al., 2009a, 2010), which is currently being implemented at several German and European car manufacturers and automotive suppliers. The following paragraphs offer a rough description of the EAWS (family). For a detailed description of EAWS please refer to Schaub et al. (2010, 2012a, 2012b). Since 2011, the application of the EAWS was neither limited to Europe nor assembly work. Thus, the 'European assembly worksheet' was accordingly renamed to 'ergonomic assessment worksheet'.

2.3.2 Tool philosophy and structure

As described in Schaub et al. (2010, 2012a) the EAWS consists of four sections for the evaluation of:

- working postures and movements with low additional physical efforts (< 30–40 N or 3–4 kg respectively)
- action forces of the whole body (> 40 N) or hand-finger system (> 30 N)
- manual materials handling (> 3 kg)
- repetitive loads of the upper limbs.

This structure is taken from and in line with relevant CEN (EN 1005-5:2007, EN 1005-2:2003/prA1:2008, EN 1005-3:2002/prA1:2008, EN 1005-4:2005/prA1:2008) and ISO standards (ISO 11226:2000, ISO 11228-1:2003, ISO 11228-2:2007, ISO 11228-3:2007). It allows a holistic evaluation of the physical workload of the 'whole body' (Schaub et al., 2009a, 2009b, 2010) and the repetitive load of the upper limbs.

In general and with one to with respect to the German BAuA and the Toyota method, IAD tools grant ergonomic load points for unfavourable conditions. Finally a traffic light, three zone rating system as described in the EU Machinery Directive (EN 614-1:2006/prA1:2008) is associated to the work situation dependent on the score achieved. Thus, the EAWS overcome the traditional concept of limiting values [e.g., NIOSH recommended weight limit (RWL) (Waters et al., 1993)].

The evaluation of the EAWS family is based on four criteria:

- the physiological and biomechanical
- the medical/epidemiological
- the psychophysical
- compliance with other internationally accepted methods and standards.

Sections 1 to 3 ('whole body') are based on a 'traditional ergonomic' evaluation approach.

For modelling of the working posture section (see Figure 8) EN 1005-4:2005/prA1:2008, ISO 11226:2000, Sämann (1970), Toyota (Koide, 1990; Eri et al., 1994) and OWAS (Karhu et al., 1981) were considered. For the force section a reference was made to EN 1005-3:2002/prA1:2008 and Schultetus (Schaub et al., 1997) and RULA (McAtamney and Corlett, 1993).

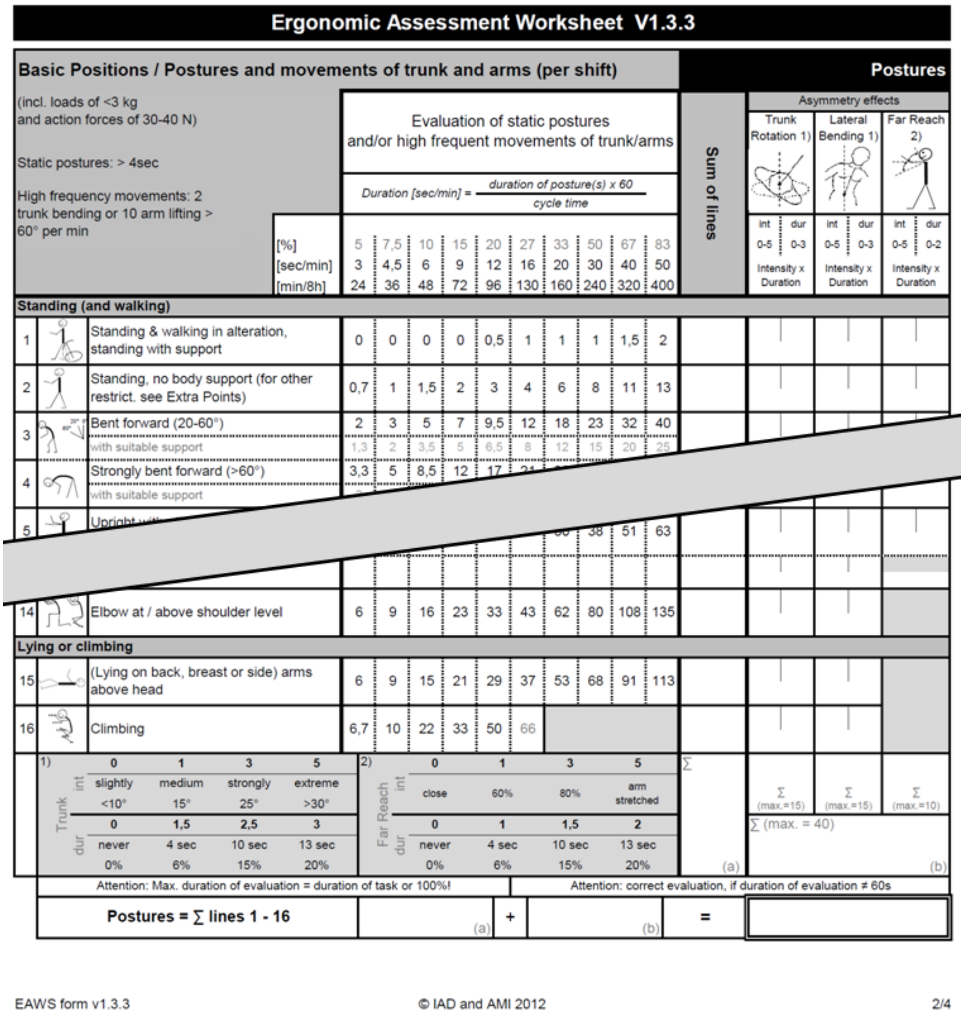
The manual materials handling section is based on BAuA's KIMs on lifting, holding, carrying, pushing and pulling (Steinberg et al., 2006, 2007a, 2007b), which serve as a national German implementation of the EU manual handling directive (Council Directive 90/269/EEC).

Section 4 (upper limbs) mainly emulates the OCRA method (Colombini et al., 2002), which is considered as a preferred method in EN 1005-2:2003/prA1:2008 and ISO 11228-3:2007 standards. Nevertheless there are some minor differences between OCRA and EAWS Section 4 (Lavatelli et al., 2012; Schaub et al., 2012a, 2012b). In addition to OCRA KIM-MHO (Steinberg et al., 2007b; Klußmann et al., 2012) was considered.

‘Whole body’ load situations are rated in one of the sections one to three either. Double evaluations are not permitted.

For validity and reliability of EAWS and related methods see Schaub et al. (2012a, 2012b).

Figure 8 Extract of the EAWS working posture evaluation



Ergonomic Assessment Worksheet V1.3.3

Basic Positions / Postures and movements of trunk and arms (per shift) — **Postures**

(incl. loads of <3 kg and action forces of 30-40 N)

Static postures: > 4sec

High frequency movements: 2 trunk bending or 10 arm lifting > 60° per min

Evaluation of static postures and/or high frequent movements of trunk/arms

Duration [sec/min] = duration of posture(s) x 60 / cycle time

		[%]	5	7,5	10	15	20	27	33	50	67	83	Sum of lines	Trunk Rotation 1) int 0-5, dur 0-3, Intensity x Duration	Lateral Bending 1) int 0-5, dur 0-3, Intensity x Duration	Far Reach 2) int 0-5, dur 0-2, Intensity x Duration
		[sec/min]	3	4,5	6	9	12	16	20	30	40	50				
		[min/8h]	24	36	48	72	96	130	160	240	320	400				
Standing (and walking)																
1	Standing & walking in alteration, standing with support		0	0	0	0	0,5	1	1	1	1,5	2				
2	Standing, no body support (for other restrict. see Extra Points)		0,7	1	1,5	2	3	4	6	8	11	13				
3	Bent forward (20-60°)		2	3	5	7	9,5	12	18	23	32	40				
	with suitable support		1,3	2	3,5	5	6,5	8	12	15	20	25				
4	Strongly bent forward (>60°)		3,3	5	8,5	12	17									
	with suitable support															
5	Upright									38	51	63				
14	Elbow at / above shoulder level		6	9	16	23	33	43	62	80	108	135				
Lying or climbing																
15	(Lying on back, breast or side) arms above head		6	9	15	21	29	37	53	68	91	113				
16	Climbing		6,7	10	22	33	50	66								

1) Trunk	0	1	3	5
int	slightly <10°	medium 15°	strongly 25°	extreme >30°
	0	1,5	2,5	3
dur	never 0%	4 sec 6%	10 sec 15%	13 sec 20%

2) Far Reach	0	1	3	5
int	close	60%	80%	arm stretched
	0	1	1,5	2
dur	never 0%	4 sec 6%	10 sec 15%	13 sec 20%

∑ (a) ∑ (max.=15) ∑ (max.=15) ∑ (max.=10) ∑ (max. = 40) (b)

Attention: Max. duration of evaluation = duration of task or 100%!

Attention: correct evaluation, if duration of evaluation ≠ 60s

Postures = ∑ lines 1 - 16 (a) + (b) =

EAWS form v1.3.3 © IAD and AMI 2012 2/4

Note: Grey area in the middle of the page represents the cut out area.

2.4 MTMergonomics® – a process language-based risk assessment

Increased global competition and changing demographic profiles lead to lean processes throughout the entire product lifecycle and the idea that a sustainable Human Resource Management was needed for the future. For the latter an ergonomic workplace and process design adaptive to the characteristics of the workforce was required. Besides this the dual European system of health and safety at work [mainly based on the EU framework (Council Directive 89/391/EEC) and machinery directive (Council Directive 2006/42/EC)] calls for an ergonomic risk assessment throughout the entire product lifecycle (Schaub et al., 2010, 2012a, 2012b). So the need for a holistic evaluation of physical workload has emerged. This led to the development of EAWS.

2.4.1 History of MTMergonomics®

In 2001, MTM and IAD developed jointly the basic idea of the MTMergonomics® approach. Considering the presence of data relevant to ergonomics in MTM building blocks, launched the idea to use MTM workload information for a basic ergonomic risk evaluation based on MTM codes.

As MTM's original focus was to plan process times, not all ergonomic data, relevant and necessary for a risk assessment were available in MTM codes, but have to be supplemented during the risk assessment process.

Bearing in mind the complexity and the uncertainties of such a project, it was decided that a feasibility study on MTMergonomics® first carried out. By the end of 2002 the basic concept for the MTMergonomics® system was successfully realised (Schaub et al., 2003).

In the following years the MTMergonomics® project was realised and a first MTMergonomics® version was available in the MTM Software TiCon® in 2005 (Schaub et al., 2005, 2009a; Schaub, 2007).

2.4.2 Tool philosophy and structure

Initially MTMergonomics® was aimed to evaluate physical workload only and was designed as a modular and open structure in order to:

1 identify, complement and describe a worker's physical workload by means of the ERGO-CODE GENERATOR based on concepts of 'geometries' (e.g., get, place) as basic steps

2 sample MTM codes to the relevant type of work (e.g., postures, forces) by means of a WORKLOAD GENERATOR and evaluate it by means of an EVALUATION GENERATOR and a selected evaluation tool

3 aggregate the evaluation outcome of several modules to a common work-station evaluation by means of an EVALUATION AGGREGATOR.

In a first step, the MTM process languages UAS and MEK were chosen as input process languages and the AAWS – and later on the EAWS – worksheet (Schaub and Landau, 1998; Schaub, 2003) as the standard ergonomics evaluation tool. This was primarily done due to the fact that the EAWS family offers a holistic evaluation of the total physical workload (see below) and gives therefore direct information to the process engineers, if ergonomics intervention is required during the design process.

However, due to its open structure 'any' other evaluation method (like OWAS or NIOSH) could be used as well. The MTMergonomics evaluation process is shown in Figure 9. Figure 10 shows the MTMergonomics system architecture. Figure 11 shows the MTMergonomics software architecture. For Figures 9 to 11 see Schaub et al. (2003). The AAWS was chosen for its holistic evaluation approach (Winter et al., 2006, 2008) and for its compliance with EU legal requirements (Schaub et al., 1996; Meyer et al., 1998).

Today ‘any’ process language, data base and data level as well as alternate evaluation tools can be implemented into MTMergonomics®. The structure of MTMergonomics software components is shown in Figure 11. A primary purpose of MTMergonomics is to support the industrial engineers during the process planning phase in the PDP concerning the realisation of ergonomically workstations and processes. MTMergonomics may be applied in the later phases of the PDP where time information concerning the tasks to be performed is available.

Figure 9 MTMergonomics evaluation process as a four step approach (see online version for colours)

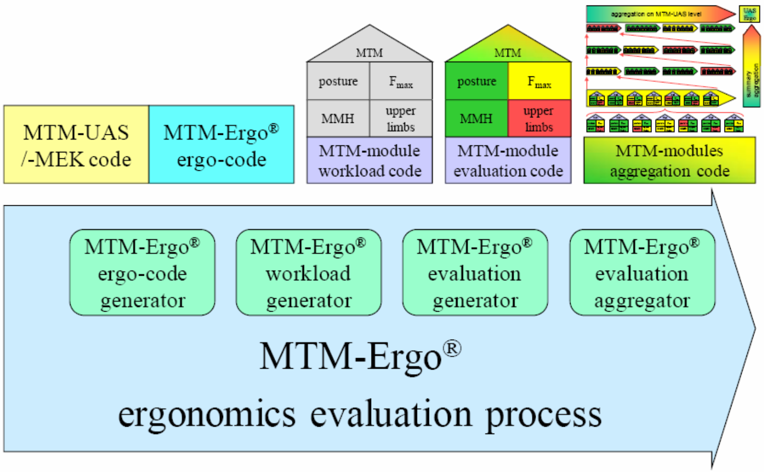


Figure 10 MTMergonomics system architecture (see online version for colours)

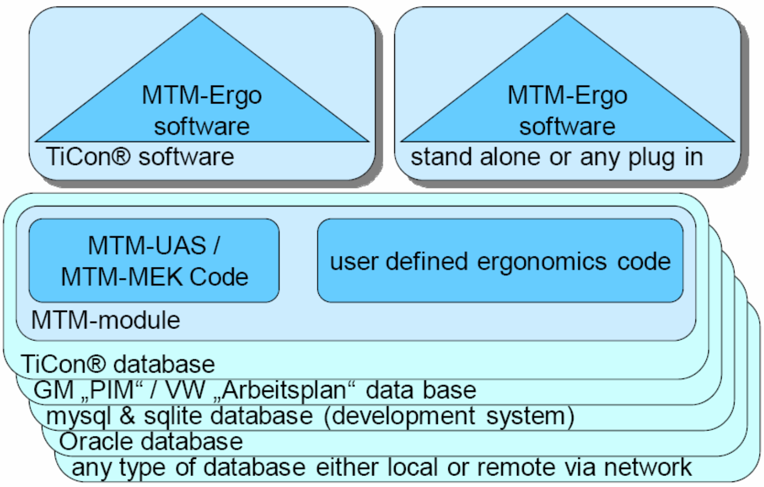
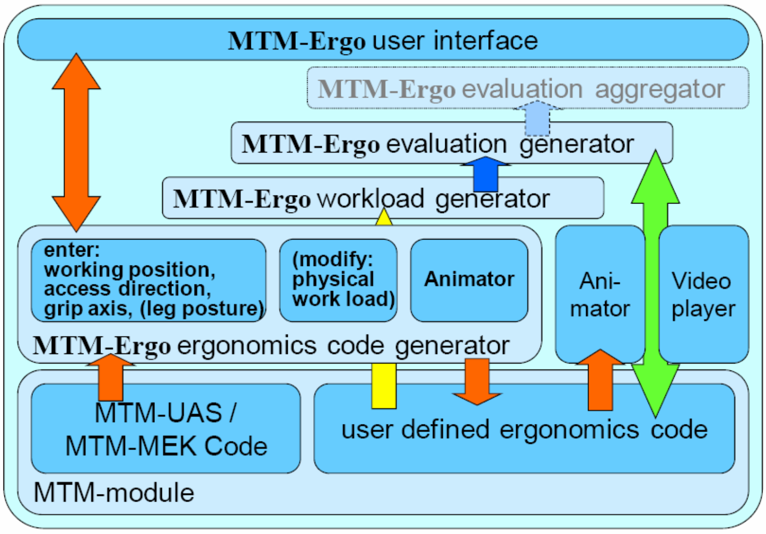


Figure 11 MTMergonomics software architecture (see online version for colours)



2.4.3 Product development processes

Product development systems especially in automotive industry are highly sophisticated and structured, and developed for an efficient, customised mass production. Experience driven 'best practice' and 'lessons learned' are key elements in the improvement of ergonomic situations and processes (Schaub, 2009). Those should be complemented by analytically structured product improvement processes, which focus on the future operator's ergonomic workload (e.g., design for assembly).

In the various stages of the PDP, ergonomic evaluations and design improvements (product as well as process-oriented) are possible. In the beginning of the process only geometric data are available which allow ergonomic evaluations in terms of reach, clearance or collision, which are basic features of DHM. In later phases information of forces and weights are give which allow first ergonomic assessments based on the number of products per shift. In later phases, when time information is available, typically when industrial engineering starts complex ergonomic risk assessments are possible (Schaub, 2009). Although the data level for ergonomic analysis and evaluation is better in the later stages of the planning process, late changes are particularly costly and critical, and provide little chance for fundamental and sustainable improvements!

Hence, both continuous improvements during production as well as proactive engineering and design in the planning phase are required for good ergonomics (Bierwirth et al., 2010).

Successful ergonomics in an enterprise requires philosophies, visions and decisions on health and safety at work. They must be part of the company structure, process and practice (Schaub, 2009). Production conditions and effects are considerably influenced by the workforce, which consists (like the PDP) of single individual life cycles. The legacy ergonomics aim of 'adapting man to work and vice versa' is subjected to new challenges, if this is considered, as 'work' and 'man' become more individual and the adaption more sophisticated (Bierwirth et al., 2011, 2012a, 2012b).

3 Application and results

3.1 EMA pilot applications

EMA has been tested in a number of pilot applications in automotive manufacturing, for instance for simulating ergonomically critical tasks in assembly and body-shop planning of a large German automobile OEM. Initial results show that EMA can reduce the effort for preparing human simulations considerably compared to manual step-by-step simulations. Most importantly, multiple pilot applications showed that EMA can be integrated in corporate software architecture being used by several car manufacturers supporting the PDP.

As a first step EMA may be used to validate the product buildability in an early concept phase, which includes verification that the vehicle can be manufactured with the given planning premises, equipment restrictions, and abilities of manual operators. In that phase ergonomic analyses can, for instance, check well-known issues of a predecessor car ('reference vehicle') and other previous models. Thereby, EMA allows the use of available CAD-data to quickly set up human simulations for comparing concept alternatives that may influence the future assembly process. Thus, in an earlier design phase part design might be revised to improve the ease of manual assembly, which may not only reduce ergonomic workload but also save production time. By enabling accurate 3D analyses of the future assembly process costs for late corrective design changes, such as part optimisations after the start of production (SOP), can be significantly reduced. Through database functions EMA also provides the opportunity to visually document good design solutions for best practices that could be used as guideline for the development of future models.

Secondly, in the phase of pre-production planning EMA may be used for the compilation and validation of the future work process. EMA supports the production planner to quickly set up a standard work sequence and generate 3D simulations for visual inspection and optimisation by utilising the features as mentioned before. Furthermore, efficient work processes are facilitated by a vast set of tools provided by EMA. Especially avoiding 'waste' (with reference to the Toyota Production System), such as ergonomic strains (e.g., far reach, bending), long walking ways, and double-handling of parts can be effectively targeted. Thus, EMA enables to compare process alternatives by means of objective quantitative analyses on ergonomics and MTM-time in early phases of pre-production planning merely based on digital product data.

The self-initiated movement of EMA easily allows the alternation of certain scenarios since movements will be carried out in reference to the 3D environment. The use of process languages, such as MTM, and a linkage of all the objects within the 3D environment thus allow a fast variation of process, product and resource (Illmann and Finsterbusch, 2012). This way planning alternatives can be easily compared in reference to MTM-time and ergonomics according to EAWS.

Finally, in the phase of series production EMA may be used for investigating product, equipment, and process optimisations before implementing changes to the production line without setting up costly production trials. In order to support the continuous improvement process after SOP, EMA allows the series planner to quickly simulate and verify the integration of new concepts in an existing production environment. Furthermore, the EMA simulation can be used to communicate evaluation results to the involved parties and reach a common sense on the final solution between the workers union, safety experts and plant management. At last, the same simulations can be used to introduce the new equipment to the workers providing a first training on the correct usage and the new work process. Taken together, using EMA's complex operations for creating human work simulations is similar to the idea of using aggregates of MTM standard times like universal automotive system (UAS). Methodologically and practically this approach provides some major benefits for the simulation of human work in industrial settings:

1 EMA introduces a standard language to digital production planning similar to MTM

2 EMA generates standard work movements that are almost independent of the planners' imagination who creates the human simulation

3 EMA saves a lot of time and effort in preparing the simulation because engineers do not have to teach the human model each single body movement – finally the purpose is not nice animation but efficient production planning.

3.2 Ergonomics assessment worksheet

Originally, the EAWS family was created for the evaluation of assembly work in automotive industries (Schaub et al., 2012a). In this field, work is carried out in short cyclic tasks (mainly 1–3 min). With respect to the short cycle times, single load peaks and prolonged awkward working postures that need recovery are absent. The EAWS family focuses on physical workload only. If job rotation occurs, all tasks performed are analysed and a time-weighted average is calculated for a final assessment as a first approach. At the moment the EAWS family cannot be used for a detailed ergonomic job rotation planning as the sequence and the load characteristic of the tasks (e.g., aggravation of fatigue or recovery aspects) is not considered. This will be one of the major challenges in the future.

In between, the EAWS family has been tested in other fields such as the paint shop, powertrain or press shop, where also longer cycle times or non-cyclic work occurred. The same applies to studies carried out in truck, bus or aviation industries or electric and metal industries (Schaub and Storz, 2003).

In all cases, 'good' results were obtained as rated by the experts involved, if the load situations were equally distributed among the shift and fatigue generating long-lasting load situations were absent as well as load peeks (Schaub and Kaltbeitzel, 2006). The evaluation of the latter load situations are clearly beyond the scope of the EAWS family.

3.3 MTMergonomics

MTMergonomics® is designed to meet the challenges from a globalising market (Schaub, 2007; Schaub et al., 2009a). In its first edition it was a suitable tool for settling ergonomics in PDPs and production systems of automotive industries.

Integrating new ergonomic evaluation tools like the EAWS (Bruder et al., 2008; Schaub et al., 2008a, 2008b) addressed new branches (e.g. automotive supplier, metal and electric industries) and companies (e.g., FIAT group, Volkswagen group) or opened the field for company specific applications like Daimler's EAB.

Based on the open concept of free definition of process language elements, MTMergonomics® is adaptable to company specific needs (e.g., Daimler's C-values), but also allows the implementation of other languages, e.g., MTM-1 or MTM-2.

New features like the comparison of workplace demands and operator capabilities allow an individual (e.g., handicapped people) or collective (e.g., elderly) adaption of man to work (Sinn-Behrendt et al., 2006).

Integrating MTMergonomics® features into line balancing and a pure design phase offers new potentials for holistic and sustainable ergonomics and thus provides good conditions for a successful competition in a globalising world.

4 Discussion

4.1 Editor for manual work activities

EMA is a new tool for simulating and editing manual work activities in digital production planning. Based on theoretical analyses, motion capturing studies, and many practical application tests, EMA improves simulation accuracy of existing man-models, such as DELMIA Human, and significantly reduces the effort for compiling human modelling studies using unique modules of complex operations. EMA enables the human model to quickly transfer standard work descriptions into sequences of natural movement – just like a real operator would do. In that sense, EMA makes the human model smarter by utilising the skills and the knowledge of a qualified worker. Finally, EMA supports production planners in analysing future ergonomic conditions and avoid physical overload proactively in order to keep the work ability of the aging workforce in manufacturing industries.

4.2 Ergonomics assessment worksheet

EAWS is still the only ergonomics evaluation method that offers an overall 'ergonomic analysis' including working postures, action forces, manual materials handling and repetitive loads of the upper limbs. It has been tested and applied successfully for short cyclic work with work cycle of about one to three minutes.

Analysis of longer cycles, like in truck or bus industries or of non-cyclic work offered also good results, when the work load was equally distributed among the shift, and long lasting fatigue generating load situations were absent as well as load peaks.

At the moment EAWS is applied at automotive original equipment manufacturers (OEMs) and suppliers, in electric and metal industries.

EAWS in its basic philosophy is a screening tool that is adapted to the relevant work situation. As production situations and philosophies are a matter of change, EAWS will also need adaptation. In order to link the method facilities to users' needs, an EAWS user group will be founded in the near future. The aim of this group is to coordinate the user needs and give input to the adoptions and further enhancements of the EAWS.

4.3 MTMergonomics

Meanwhile much experience has been gathered in the application of MTMergonomics (Schaub, 2009). It is easily applicable, but due to the large number of inputs the application is exhausting when implemented, as all UAS codes have to be manually completed by means of the ergo-code generator. However, it is possible to initially set a 'standard' ergo-code for all UAS codes, and alter all the (groups of) codes that differ from the 'standard'.

Linking MTMergonomics to a CAD system as used at the major automotive OEMS would substantially cut down the evaluation times, as all workplace data that have to be input manually into MTMergonomics are available in the CAD systems. First approaches to link MTMergonomics and CAD systems have been undertaken, but due to the early project status no publication is available on this topic at the moment.

MTMergonomics is not a DHM in its classical meaning. It does not offer biomechanical evaluations or an extended anthropometric analysis. However it is possible to select the 5th, 50th and 95th unisex anthropometric body height percentile for the European population, so that risk assessments may be carried out for the 'total target population'. The animator offered allows the user to control the sequence of working postures during the analysed working task. As a matter of fact, it is not a simulation of human movements, but a sequence at defined positions in an MTM code. For example a UAS 'pick and place' would consist of two 'geometries' describing the postures during the 'pick' and 'place' operation. No movement simulations are done in between the 'pick' and 'place' nor in between consecutive UAS codes. As this feature was only designed for a rough 'motion' control, support from DHM simulation systems like EMA would be helpful.

The MTMergonomics core competence is to generate a very detailed description of the working task by means of an (MTM) process language and to link it with an ergo-code generator that offers input to 'any' evaluation tool.

4.4 A vision

A vision that is not too far from now would be the integration of MTMergonomics and EMA (including EAWS) into the CAD systems of the automotive OEMs. Such an integrated tool would offer a proper workings task simulation based on the EMA simulation features, combined with MTMergonomics task description and evaluation (EAWS) facilities. The CAD systems integration would eliminate the need for manual input of data that are already available in the CAD systems. This is one of the major restrictions in application and a time consuming effort which reduces the willingness to apply these tools. With the integration of EAWS in DHMs a first step has been done in this direction. The 'growing together' of DHM, EMA, MTMergonomics and EAWS is a major challenge that still lies ahead; visions for that 'growing together' do already exist.

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