

Digital Human Modeling Simulation Results and Their Outcomes in Reality: A Comparative Study within Manual Assembly of Automobiles

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ABSTRACT

The objective of this study was to examine to what extent ergonomics simulations of manual assembly tasks correctly predict the real outcomes in automotive assembly plants, and if recommended measures originating from ergonomics simulations are considered. 155 ergonomics simulation cases done by nine simulation engineers at Volvo Car Corporation in Gothenburg were used in the study. The evaluations of the ergonomics conditions in reality of the cases were done by six professional ergonomists working in the company. The results show that digital human modelling tools are useful for providing designs for standing and unconstrained working postures as well as for the design of various auxiliary devices and their needed space for movements. The study also identifies areas that require additional development in order to improve the digital human modelling tools' ability to correctly predict a work task's real outcome. Moreover, a better feedback of product and process changes, and a more careful order description to the simulation engineers, would improve simulation results in current and future projects.

1. INTRODUCTION

Virtual technology using DHM-tools is increasingly the major means used to perform ergonomics analyses and

analyses of assemblability of manual assembly tasks in the automotive industry. Virtual technology allows ergonomists and engineers to perform virtual builds, and the rapid adoption of virtual tools pose an opportunity to integrate considerations of ergonomics into early design stages (Mathiassen *et al.*, 2002). The tools are applied in the design, modification, visualization and analysis of human workplace layouts and / or product interactions.

Several studies have been carried out to validate different DHM-tools for ergonomics evaluation in-vehicle manufacturing (Loczi *et al.*, 1999; Nilsson, 1999; Vogt *et al.*, 2005). All these studies show that the predictions of the different tools are fairly accurate, but there is still a need for improvements of the tools, not the least from a usability and organisational point of view. Considerably less research has been conducted to investigate the end users' experiences with the DHM-tools and the tools ability to correctly predict and evaluate manual assembly tasks (non-seated tasks and tasks mostly performed outside of the vehicle). Gill and Ruddle (1998) presented an early work describing the general benefits of the use of a DHM-tool for ergonomics assessments. Dukic *et al.* (2007) performed a study of the evaluation of ergonomics using virtual tools in a pre-production phase at a car manufacturer; that study focused especially on the verification of visual demands in assembly work. Lämkuil *et al.* (2008) presented a comparative study of manikin (digital human model) posturing within and

between simulation engineers using a DHM-tool for manual automotive assembly cases.

DHM-tools are complex and using them requires expertise in different fields. It is necessary to know ergonomics but also to have CAD skills and to have a detailed knowledge of the various features of the product being designed / evaluated (Lockett *et al.* 2005). Furthermore, several researchers and end users claim that an efficient use of the DHM-tools can not be attained until a proper process and organization structure is developed around the use of the tools (Green, 2000; Ziolek and Kruithof, 2000; Sundin, 2001; Hanson *et al.*, 2006).

The objective of this study was to examine to what extent ergonomics simulations of manual assembly tasks correctly predict the real outcomes in the plants and whether recommended measures originating from ergonomics simulations are taken into consideration. Another purpose of the study was to analyze and categorize possible explanations of deviations between simulation results and the real outcomes in the plants.

2. METHODS AND MATERIAL

2.1 MATERIAL - The study included 155 ergonomics simulation cases. 29 of the ergonomics simulation cases were selected in a retrospective approach; they were all related to known and reported existing assembly tasks with unacceptable ergonomics conditions in the plants. 126 of the ergonomics simulation cases were selected in a prospective approach, i.e. they were all simulated long before (several years) the tasks were put in operation. They were all linked to simulation results indicating the whole range of evaluation results of ergonomics conditions used in the study: unacceptable (high risk, red), acceptable (some risk, yellow) or target (no risk, green).

The cases involved assembly operations for 87 the four Volvo car models S80, V70, XC70 and XC60. All ergonomics simulations were performed by nine simulation engineers in the Trim and Final simulation group at Volvo Car Corporation (VCC) in Torslanda, Gothenburg. The ergonomics simulation cases were all stored in and extracted from VCC's simulation order and report database. The simulations were done in the DHM-tool *eM-Human (with RAMSIS)* from Siemens / UGS. The assembly tasks were carried out in Volvo's Gothenburg plant in Torslanda, except for the tasks related to the car model XC60. The production plant for XC60 is Volvo's Ghent plant in Belgium. During the gathering of material for this paper the mass production of XC60 had not yet started; thus the XC60-tasks carried

out in the plant were observed during XC60's Pre-Try-Out (PTO). PTO means that all requirements for assembling of vehicles in plants with the production equipment are reached. The PTO is used to verify the production process prior to the assembly plant acceleration starts.

2.2 THE WORK PROCESS FOR PERFORMING ERGONOMICS SIMULATION - VCC uses a generic work process for performing digital human model analysis suggested by, among others, Green (2000) and Hanson *et al.* (2006). The work process includes the following seven steps: 1) understanding the task, 2) understanding the work environment, 3) understanding the worker population, 4) understanding the limits of the software used, 5) performing the analysis, 6) analysing and applying judgements to the results, and 7) reporting the results of the analysis.

The simulation engineers are performing the first two steps together with the customers (simulation orderers). During these steps the virtual environment is created and the simulation engineer is informed about the purpose of the work task and its different prerequisites. In step three the anthropometry of the digital human models are determined. VCC uses the commercial DHM-tool *eM-Human (with RAMSIS)* from Siemens / UGS, the typology of which is based on the knowledge that the characterising measurements length, proportion and corpulence of an individual is sufficient to give an prognosis of all other body dimensions for this person (Speyer, 1996). These three measurements are defined by the key measurements stature, sitting height and waist circumference. Based on these three key measurements, *eM-Human* then derives statistically likely values for the other measurements of the body. For all simulations VCC uses three manikin models (with anthropometric data for German females and males, year 2000) according to Speyer's (1996) RAMSIS typology, see Table 1. (So far no anthropometric data are available for Swedish or Belgian workers in the DHM-tool used.)

Step four is the step where the competence of the simulation engineers has a crucial importance for creating an accurate and realistic input material for analysis, since the step is performed solely by the engineers themselves. Step five to seven are done by the simulation engineers together with one or several ergonomists. The ergonomists are responsible for performing the analysis and applying judgements to the results.

Table 1. Manikin characteristics used in the study based on Speyer's (1996) RAMSIS typology. (Anthropometric data for German females and males, year 2000).

Manikin characteristic	Stature [mm]	Waist Circumference [mm]	Sitting height [mm]	Weight [kg]	Approximate percentile (Stature)
Female very short – medium waist – medium torso	1525,8	777,6	820,6	58,2	5th
Male medium length – medium waist – medium torso	1742,5	888,6	916,8	76,1	50th
Male very tall – short waist – short torso	1871,6	747,4	941,3	69,3	95th

Table 2. Four of a total of eight ergonomics requirements in VCC's ergonomics requirements standard (VCS 8003-29 2006) were dealt with in the selected simulations.

Ergonomics requirement	Definition	Test method
Working height	Work from underneath/Work at and above shoulder height must not occur both if it is carried out at a sitting or standing position	Simulation with DHM-tool and/or evaluation on physical mock-up/car
Working distance	The objective is to perform the operation in the green zone in the distance diagram, the yellow zone can be conditionally accepted. Red zone is not acceptable. In general terms a work distance exceeding 500 mm from operator's front hip bone, shall not occur.	Simulation with DHM-tool and/or evaluation on physical mock-up/car with the right working heights
Clearance	There must be enough space for the operator, i. e. hands, machine, components for assembly at the spot for assembly. When sharp edges, clearance must not be less than 25 mm for hands/arms.	Simulation with DHM-tool with the 95 %-ile male hand and/or test on physical mock-up/car
Hidden assembly	Parts and/or components or operations must be able to be seen or differentiated when assembled or performed. Hidden assembly may be permitted provided fully technical guidance can be arranged in order to facilitate a correct assembly.	Simulation with DHM-tool, use the vision module in the programme to get a field of vision.

2.3 STUDY DESIGN - The study was divided into four phases: 1) retrospective approach for selection of ergonomics simulation cases, 2) prospective approach for selection of ergonomics simulation cases, 3) classification of ergonomics conditions of simulations and real outcomes, and 4) analysis of possible

explanations behind deviations between simulation results and the real outcomes in the plants.

2.4 CLASSIFICATION OF ERGONOMICS CONDITIONS OF SIMULATIONS AND REAL OUTCOMES - The evaluation of ergonomics conditions

of eight different ergonomics requirements in VCC's ergonomics requirements standard (VCS 8003-29, 2006) were originally considered in the study. However, only four of these were considered as being possible to successfully address through the use of a DHM-tool, i.e. working height, working distance, clearance and hidden assembly. Definitions and test methods are given in Table 2. Thus, *only these requirements* were included in the comparison between simulation results and the real outcomes in the plants. (The other four were weight, sharp edges, assembly force, and feedback.)

The 155 ergonomics cases were classified according to VCC's ergonomics requirements standard which is based on a multi-zone system consisting of three levels. The classification of ergonomics condition was applied only to each job task and based on the number of ergonomics requirements not met. Consequently, there are 155 comparisons, rather than 620 (155 x 4) comparisons.

The three levels in the multi-zone system are:

- 1) Red (unacceptable) – The task is clearly hazardous and implies a great risk of injury which must be prevented,
- 2) Yellow (acceptable) – The task implies a certain risk of disorder depending on number of movements or the duration of the posture. The time aspect is always important; no work posture which can be assumed naturally is intrinsically dangerous to health – the risks occur if the posture is assumed too often or too long, therefore a yellow classified task might be acceptable with immediate remedial actions such as work rotations to physically differing tasks, the use of well adapted work techniques and feasible lifting / aid equipments (AFS, 1998),
- 3) Green (target) – The task entails negligible risks and should be manageable for all healthy employees.

2.4.1 Evaluation of the ergonomics conditions of the simulated tasks - The evaluations were carried out based on three evaluation tools integrated in the DHM-tool (joint configuration, work distance / hand position and field of vision) *and* on the ergonomists visual judgements. Each evaluation was done by at least three of the six participating ergonomists. All ergonomists had experience of DHM-tools, either hands-on experience (computer user) or experience as interpreters of visualizations.

Evaluation of joint configuration. VCC has developed a web-based ergonomics-report tool (see Högberg et al., 2008). This tool gives all joint configurations of the manikin in the DHM-tool according to the nomenclature used within the ergonomic-community (e.g.: flexion, extension, adduction, abduction, rotation, supination, pronation, etc). The manikins' joint values are compared to VCC's ergonomics requirements standard which is based on Petré's (1968) maximum joint values, and

gives a classification of the values by using the three level multi-zone system (see above). The report tool gives the joint values of neck, back, shoulders, elbows, hands, hips, knees, and feet.

Evaluation of work distance / hand position. The web-based ergonomics-report tool also indicates whether the maximum recommended reach distance and hand position are violated or not according to AFS' provision 1998:1. In general terms a work distance exceeding 500 mm from the assembly worker's front hip bone shall not occur. The hand position indicates both work distance and work height.

Evaluation of field of vision. DHM-tools provide the opportunity to see through the manikin's eyes, and a view obtained via this function is a very natural way for visual inspection of human workspace design (Hoekstra, 1993). For each simulation the simulation engineer captured the manikin's field of vision to give the ergonomists information by means of which they could judge how well the visual requirements (Table 2) were fulfilled – the value of fulfilment is either bad (red) or good (green).

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2.4.2 Evaluation of the ergonomics conditions of the real outcomes in the plant - The evaluation was based on SWEA's physical ergonomics provision (AFS, 1998) giving physical ergonomics requirements in general terms. The appendix of the provision contains guidelines for work postures, duration of work cycles, lifting requirements and relevant conditions which worsen or improve the harmfulness of a work posture. Due to the generic formulations, it is important that the evaluations are performed by persons with knowledge and experience of ergonomics evaluation, preferably OHSO personnel, such as ergonomists, physiotherapists etc. In this study, two ergonomists from the OHSO in the Torslanda plant evaluated the Torslanda related tasks and two ergonomists from the OSHO in the Ghent plant evaluated the Ghent related tasks. In order to prevent the evaluating ergonomists from being influenced by the simulation results they were all blinded to these results.

The evaluations were done on a work task basis, looking at individual assembly workers, observing work flows and basing evaluations on observed high-risk work postures and frequency of occurrence. Each work task was commented in a results protocol and work posture, reachability, and lifting requirements were given a rating of red, yellow or green, according to the VCC's ergonomics requirements standard (VCS 8003-29, 2006). Each observed assembly worker was asked to comment the visual condition in terms of bad (red) or good (green) - there was no yellow level for visual condition.

2.5 PROCEDURE OF COMPARISONS BETWEEN SIMULATION RESULTS AND THE REAL OUTCOMES IN THE PLANTS - The results of each simulation were compared with each corresponding real outcome in the plants. The comparisons were matched according to following list:

- Joint configuration (from simulation) was compared with work posture comments (from evaluation of real task)
- Work distance (from simulation) was compared with reachability comments (from evaluation of real task)
- Hand position (from simulation) was compared with lifting requirements (from evaluation of real task). Hand position and lifting requirements also give information about the work height
- Captured field of vision (from simulation) was compared with the operator's opinion on the visual conditions during the assembly task (from evaluation of real task)

2.6 ANALYSIS OF POSSIBLE EXPLANATIONS BEHIND DEVIATIONS BETWEEN SIMULATION RESULTS AND THE REAL OUTCOMES IN THE PLANTS - During the analysis phase explanations to the deviation in ratings of ergonomics conditions between the simulation results and the real outcomes in the plants were sought after. A number of possible explanations were defined and compiled together with the simulation engineers, the ergonomists, and the manufacturing engineers. A summary of the explanations is listed in Table 4. In total, 48 manufacturing engineers were orderers of the 155 simulation cases. 17 of the manufacturing engineers had ordered four, or more, simulations and were selected to participate in the study. In total, 90 of the 155 simulation cases had been ordered by the 17 participating manufacturing engineers.

2.7 INTERVIEWS - All participating simulation engineers, ergonomists and manufacturing engineers were interviewed during the study. The simulation engineers took part in a semi-structured group interview where they answered questions regarding their experiences of the use of the DHM-tool and the order-routine of simulation cases. The ergonomists were interviewed in parallel to their visual evaluation of the ergonomics simulations. They answered questions

concerning possible reasons for differences between simulation results and the real outcomes in the plants. Each manufacturing engineer was asked to give comments about their specific simulation tasks / simulation orders. Both ergonomists and manufacturing engineers were asked to give their opinion of the DHM-tool's advantages and disadvantages.

3. RESULTS

3.1 THE RESULTS FROM THE RETROSPECTIVE APPROACH – All of the 29 manual assembly tasks with red ergonomics conditions had been simulated and stored in VCC's simulation order and report database. 18 of the simulation cases (62%) reported the ergonomics conditions as red and nine simulation cases (31%) reported the ergonomics conditions as being yellow. In two simulation cases (7%) the simulation results were classified as green.

3.2 THE RESULTS FROM THE PROSPECTIVE APPROACH - For 23 of the 126 ergonomics simulation cases green ergonomics conditions were indicated. 22 of these cases were also found to be green in the reality, while the 23rd case was evaluated as being yellow. Of the 103 ergonomics simulation cases that had indicated bad ergonomics conditions, 57 cases indicated red conditions and 46 indicated yellow conditions. For 13 (23%) of the 57 cases indicating red conditions also the real assembly tasks were classified as being red. 32 cases (56%) of the 57 red cases were classified as yellow in the plant, and twelve cases (21%) were classified as green cases. (See Table 3.)

Table 3. Summary of the results from the prospective approach. Numbers in boldface indicate agreement between ergonomics simulation result and evaluated ergonomics condition in the reality.

	Evaluated ergonomics condition in the reality (in the plant)			
Ergonomics simulation result	Green	Yellow	Red	Total
Green	22	1	0	23
Yellow	21	22	3	46
Red	12	32	13	57
Total	55	55	16	126