INTERACT – Interactive Manual Assembly Operations for the Human-Centered Workplaces of the Future

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INTERACT

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Summary:
Description of the INTERACT requirements regarding the generation, manipulation and improvement of digital human simulation models used for planning human work tasks. This deliverable is the main outcome of Task 1.1.

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Contents

1. EXECUTIVE SUMMARY

The content of this document is the outcome of INTERACT Task 1.1 "Requirements on efficient manual assembly model generation and interaction". The main purpose of this document is to:

- Identify important problems in current practice in terms of Digital Human Model (DHM) based model generation and modification
- Define an approach for measuring the success of INTERACT DHM motion simulation and also provide a baseline to compare INTERACT achievements.
- Define requirements for efficient model generation and modification

The document is structured as follows:

- Chapter 3 provides an analysis of the current practices and state of the art. A list of key problems identified in current industrial practice is reported. In the Appendix I, a detailed list of business requirements is provided.
- Chapter 4 provides a description of imk automotive EMA tool, which will provide the baseline for comparing INTERACT achievements in the project. Moreover in chapter 4, a list of success criteria and an approach to measure them are presented. Special focus is provided for measuring the adequacy and the quality of DHM based simulation for digital validation. These criteria will be used for comparing INTERACT achievements to the EMA (for most aspects) and DELMIA V5 (for some aspects).
- Chapter 5 presents key features and key system requirements for the INTERACT DHM based simulation. The requirements focus on the following aspects:
    - Elementary motions to be simulated
    - Derivation of a sequence of elementary motions from planning texts
    - Model constraint generation
    - Motion synthesis
    - Model interaction
    - Model simulation / animation
    - Non-functional requirements

Primary conclusions / results include the following:

- The main result of this deliverable is the list of requirements and key features for the INTERACT motion simulation developments to take place in WP2 "Best-fit simulation of manual assembly using sensor data". The system requirements and key features are derived by analyzing the current practices and the INTERACT user requirements provided in the Annex.
- The analysis of the state of the art has indicated that there is a high potential in using the principles of the morphable graphs approach for a baseline in DHM motion generation.
- The list of success criteria will be used in WP 6 "Industrial Pilot Cases, Demonstration and System Validation" for assessing performance of the INTERACT motion generation and synthesis approach.

2. INTRODUCTION

The aim of the deliverable is to identify and report the requirements for generation of virtual models that are used to represent and study manual operations including assembly and warehousing activities.

These requirements are gathered through the analysis of the current industrial practices in manual assembly operations. The final target is to record areas for improvement in the current practices and to set the basis and technological targets for the INTERACT modules that will be responsible for building the human simulation models.

The capturing of the requirements will be mostly based on a) the analysis of existing tools/techniques for model generation and the evaluation of their capabilities in terms of data input, efforts required and time and b) on the analysis of existing practices that are considered by the end users when creating such models for evaluating and optimizing their processes.

3. Current practices and state of the art in manual processes model generation and interaction

3.1. Current practices

Production systems need to adjust to a continuously changing market. Trying to keep up with market demands, OEMs such as automotive and professional white goods are offering an increasing number of customized products and their variants. In order to address faster time-to-market requirements by modern production systems are faced with faster and more 'right-first-time' ramp-up processes, which can manage shorter production planning cycles and increasing product variety, as well as the need to include new variants into existing production lines (Michalos et. al. 2010). Moreover, considerable attendance has been given by the industry to minimize production cycle time, while considering fatigue, safety and health issues of the human operators, especially in manual assembly processes (Chryssolouris 2006). Therefore, it is necessary that a considerable amount of ergonomic factors be analyzed and evaluated in order for injuries and safety problems to be avoided. The traditional method of analyzing complex manual or hybrid production process is the implementation of a product's complete physical mockups, the assembly workspace and the real workers used, in different combinations, in order for the optimum set-up to be produced. This is both time consuming, and costly; characteristics that do not conform to the goals of modern industry. In automotive industry prototype building serves as an opportunity to evaluate, verify and optimize production planning (Manns and Arteaga 2013). The assembly planning team conducts several prototype builds before the start of production. During these prototype builds, the planner reads the planned processes out loud, and a worker interprets and follows the instructions, while experts from different fields perform different evaluations and verifications. The goal of these builds is to achieve an optimal production process preparation through which efficient, ergonomically optimal, stable and robust processes are defined, product quality is guaranteed, and production ramp-up can be completed faster. As product variety increases, it becomes more difficult and costly to build physical prototypes of all variants. However, reducing prototypes reduces the number of manual assembly process verifications that can be done using prototypes (Manns and Arteaga 2013).

However nowadays, the use of the Digital Human Modeling (DHM) software integrated into the Virtual Manufacturing Software (VMS) is common practice in many industries, especially those producing complex products (e.g. vehicles and aircrafts) or working with complex production and maintenance processes. A number of DHM tools have been made commercially available to support human factors and the ergonomics analysis in a product, process and workplace design (e.g. Siemens 2014 and Dassault Systemes 2014). The DHM tools use computer manikins (i.e. digital humans) as representations of the human operators inserted into a synthetic or virtual environment to facilitate the assessment of process performance and safety. Apart from the human representation in a digital format, the DHM software tools are usually equipped with a certain functionality that is suitable for considering and analyzing human factors and ergonomics aspects. The availability of accurate digital models and simulation tools has significantly reduced development time and cost by being able to identify and correct problems before any physical prototypes are built. For example in automotive assembly planning digital buildability check is a well-established process, in which digital models of the vehicle's parts are checked for geometric consistency, thus guaranteeing that all parts can be assembled before any prototype parts are manufactured.

Unfortunately, in practice, such digital assembly verifications mainly comprise static analyses of buildability and accessability. This is due to **time consuming modeling, inflexibility to changes on process,** and product, and to often occurring unnatural movements of the DHM if dynamic processes are modeled. In order to successfully conduct DHM simulation in the design process, generating human motion is one of the most important issues to be addressed. Forward and Inverse Kinematics are used to generate motion, such as human walking, or a library of predefined postures may be available for users. . In forward kinematics, instead of specifying positions, the motion animator specifies parameters that condense the essence of the motion and allow its individualization. In inverse kinematics, if the position of the final effector is given, the calculation of the intermediate links is automatic. Typically, the user defines a number of key frames, i.e. static postures. Then DHM interpolates between every pair of key frames to generate in between postures that depict the whole movement of the DHM. Following this approach, this is the current practice, modeling a simple task, such as walking and picking a part form a bin, requires the definition of various key frames. However, if changes on the scene are required, e.g. a new position of the bin or a new version of the part, new modeling of the whole process is usually required. Even after carefully modeling the key frames, unnatural behavior of the DHM's movements could arise. So as to avoid this issue, usually more key frames need to be defined, thus increasing modeling time (Manns and Arteaga, 2013). In a similar manner ergonomic assessment is primarily provided as a static analysis of the task at hand, i.e. one can create a static ‘‘snapshot’’ of the posture or situation to be evaluated and then perform an analysis using the DHM tool (Alexopoulos et. al. 2013).

Another, technique for motion generation and simulation of manufacturing and assembly tasks is Motion Capture (Hartel et. al. 2010). It is a technique to record and digitally present human body movements. By attaching markers or sensors on the human body, cameras or receivers can capture the motions of body segments. Comparing to the kinematics approach, generating motion through motion capture system has the advantage of describing realistic human motions and requires less modelling time. However, typical Motion Capture systems, such as optical and magnetic ones, are a) expensive and b) are very difficult to setup and operate in an industrial working environment and c) their generated motion neither be edited or adapted to different task constraints nor be compared to simulated motions on the fly or offline in a time efficient manner. Consequently, Motion Capture is not effectively used for industrial process design although its benefits for generating realistic digital simulations are widely recognized.

Alternatives, like imk automotive's EMA, address the time consuming and inflexible approach of classical DHM tools by allowing a more abstract modeling of the DHM movements and its interactions (Manns and Arteaga 2013). This approach is based on the decomposition of tasks into basic operations and the use of parameterized movement generation. The underlying movements appear more natural due to the fact that these were synthesized by recording and analyzing the movements of real workers executing diverse manual tasks (Fritzsche et al. 2011). However, as we move away from detailed but time consuming DHM based process modelling then we lose a lot in terms of simulation quality (for example in terms of simulation realism).

There are two main industrial pilot cases within the INTERACT project. The first is one is related to digital automotive production planning verification, the second one to warehouse component handling within the area of professional white goods. Both pilot cases are shortly described in D1.2.1 “Requirements on monitoring of manual assembly operations”. A complete description of the project pilot cases is provided in confidential deliverable D1.4.1 “Industrial pilots definition”.

The analysis of the current practice in industry and the definition of the pilot cases has indicated the key problems of using DHM based simulations in current practice. Existing simulation tools have proven to be difficult to cope with, especially with respect to the aspects summarized in the following Table 1.

Key Problems Identified in Current Industrial Practice	**Importance**
Too high modeling time required by the user.	Critical
Displayed process could not be changed on the fly. Instead editing of the model requires even up to 1-2 weeks.	Critical
Unlike with the evaluation using physical parts, during the use of virtual models there are less solution suggestions.	High
Ability to modify the digital model using sensor data from some motion capture session.	High
High realism of the model that satisfies needs especially of ergonomics experts. There should be minimum trade-off between modelling time and realism.	High
Forces and their impact on workers were not displayed	High
It is not possible to compare 3D human simulation process models with real	Average

human process execution both on the fly and off-line (in a time efficient manner for the later).	
3D human simulation models should be interactive and flexible so that they can be altered by different process/product designers by him/herself without the need of an expert with DHM modelling skills.	Average
The users of the models do not have the ability touch parts and get a real feeling of the requirements for handling/assembling the part	Average

Table 1: Key problems for efficient 3D human simulation models generation and interaction

Following the identification of the key problems for using DHM based simulations for analyzing the industrial processes a detailed list of requirements has been generated as an outcome of the requirements gathering phase. The comprehensive list is provided in Appendix I: USER REQUIREMENTS CATALOGUE FOR DHM BASED MODEL

3.2. State of the art

3.2.1. Motion generation and motion synthesis

Manual assembly stations incorporate complex and time-consuming operations that involve human interaction with different kinds of tools and materials. DHM tools have been developed to characterize human locomotion and to simulate human-system interaction (Mavrikios et. al. 2007, Pappas et. al. 2007). In order to successfully conduct DHM simulation in the design process, generating human motion is one of the most important issues to be addressed. Forward and Inverse Kinematics are used to generate motion, such as human walking. These systems are based on biomechanical and biological studies. In forward kinematics, instead of specifying positions, the motion animator specifies parameters that condense the essence of the motion and allow its individualization. In inverse kinematics, if the position of the final effector is given, the calculation of the intermediate links is automatic (Chryssolouris et. al. 2001). Other approaches for motion simulation utilize a database of motions for motion modelling and prediction (Park et al. 2004) or combine existing motions in order to generate new ones. Several approaches use statistical analysis (e.g. regression) on motion-captured data in order to form predictive models for a sequence of postures. Motion adaptation/retargeting techniques, influenced by computer graphics ones have been used in order to generate new motions for different characters with the existing captured motions. These approaches consider motion as a set of signals and apply signal-processing techniques to them (Bruderlin and Williams 1995, Witkin and Popovic 1995). Retargeting techniques usually re-use motions created for one character for controlling the motion of others, so as to preserve as many as possible of the desirable properties of the original motion. In that case, constraint optimization techniques are used to impose valid postures (Gleicher 1998) or multiple-objective optimization has been proposed in (Yang et. al. 2004). One popular data-driven approach is motion graphs, which represent allowable transitions between poses (Kovar et al. 2002; Safonova and Hodgins 2007). Motion graphs create an animation by cutting pieces from a motion database and reassembling them to form a new motion.

In (Heck and Gleicher 2007) they present the parametric motion graph, an example-based motion synthesis data structure. A parametric motion graph describes possible ways to generate seamless streams of motion by concatenating short motion clips generated through blending-based parametric synthesis. Blending-based parametric synthesis allows generation of any motion from an entire space of motions, by blending together examples from that space.

In order to overcome drawbacks of the motion graphs concept, (Min et. al. 2012) have developed a generative motion model that is compact and amenable for motion analysis and synthesis. Elementary motions such as right stance or left stance are represented by parameterized statistical distributions. These distributions form the nodes of a graph (called morphable graph or motion graph++), in which transition probabilities of the parameters are represented by the vertices, i.e. if in a walk the right stance is done slowly, the following left stance is likely to be slow, too (Figure 1). This representation allows describing infinite elementary motion styles within one node and therefore allows efficient storage and synthesis with huge and heterogeneous motion databases. These styles are differentiated from high-level structures, that are derived from traversing different graph paths. Min et. al. have demonstrated that their system can generate a wide range of style variations, including functional variations (e.g. locomotion speeds, step sizes, uneven terrains, and turning angles).

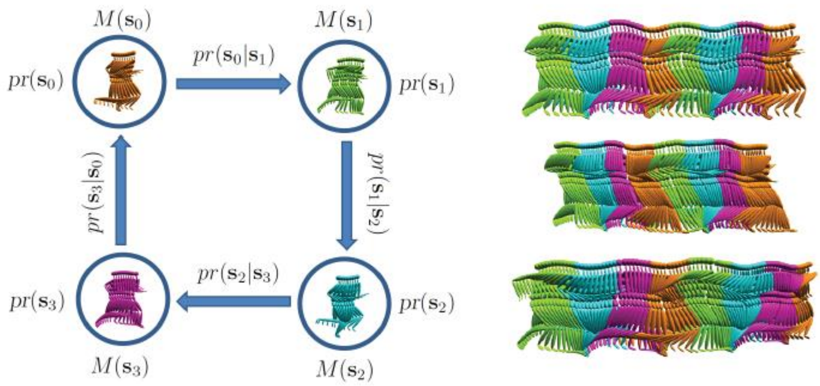

Figure 1: A morphable graphs model for running (Min et. al. 2012)

3.2.2. Ergonomics Assessment

Scientific results show that computer manikins are viable tools for the verification of ergonomics early in a development process and for helping detect many problems prior to physical pre-series. There is a considerable amount of research that focuses on the application of the DHM technology, incorporated in VMS for the evaluation of ergonomics in industry by using commonly available methods. Demirel and Duffy (2007) have investigated the use of DHM integrated within PLM for three industrial cases and their results indicated that the DHM tools have the potential to improve design challenges during product development and provide control of the entire process of designing and analyzing a product before ever being launched. Mavrikios *et al.* (2007) and Pappas *et al.* (2007) have applied static posture analysis, in a real-life scenario, by using ergonomic tools provided by DHM and they proposed countermeasures in order to improve working “comfort” in manual assembly tasks.

Dynamic ergonomics analysis in a VMS was presented in Rhen *et. al.* (2011a) and Rhen *et. al.* (2011b). It is illustrated how time significant wrist exposure data can be obtained from a DHM and may be used for ergonomics assessment. An assembly task is analysed with the help of DHM tool and they propose an evaluation model where RULA’s thresholds are used in combination with time-dependant information regarding wrist flexion/extension. Ma *et. al. (2010)* propose a framework to evaluate manual work operations with the support of motion tracking, DHM and the Maynard Operation Sequence Technique (MOST) motion–time method. Their framework utilizes a mechanism of automatic motion recognition but their work focuses on assessing manual work efficiency, using MOST, rather than on assessing ergonomics related risks of manual operations. Alexopoulos et. al. (2013) presented ErgoToolkit, which implements ergonomic analysis methods, into digital tools for ergonomics, integrated into state of-the-art virtual manufacturing software DELMIA V5. Their approach implements the Automotive Assembly Worksheet (AAWS) method presented in Winter et al. (2006).

3.2.3. Controlled Natural Language

Controlled Natural Languages (CNLs) are subsets of natural languages such as English. Not all words are permitted, not all grammatical constructions are allowed, and certain stylistic rules are in place to guide the writers. Why were CNLs developed as alternatives to natural languages?

Natural language statements are often ambiguous. Consider "Sue met Tania, because she wanted to apologize". Who wanted to apologize? Usually there is a preference to subject reference, i.e. Sue, but there is a valid reading saying that Tania wanted to apologize. CNLs usually interdict the use of pronouns. "Sue met Tania because Tania wanted to apologize" would be a valid CNL expression.

Natural language statements are often unspecific. Consider "The door must be opened before entering" or "The screw driver should be placed near the screws". In both examples, the actors are not mentioned. In technical writing, actors are essential which is why CNLs usually forbid the use of modal verbs and of passive constructions. "Open the door before entering", or "Place the screwdriver near the screws" are valid expressions in many CNLs.

Natural language statements are often very complex. While parsing free text has made tremendous progress, there are still constructions that cannot be parsed successfully yet. A CNL is defined in such a way that only grammatical expressions are allowed and that these expressions can be guaranteed to parse correctly. By the same token, translatability from one language into another one is supported by CNLs. This is a frequent necessity by companies selling technical devices to international customers.

For computer usage, CNLs were invented since the early 1970s, with the Caterpillar Fundamental English being a most prominent example. Boeing has a CNL to describe aircraft manuals. Another famous CNL is AECMA Simplified English. Siemens has created a German CNL. Nothing is nown about the detailed definitions, as these are considered proprietary knowledge by the respective companies. An overview of the CNL topic is given by Wojcik and Hoard (1997), and with a view on ontology editing, by Funk et al. (2007).

For INTERACT, CNLs are needed for all of the above reasons. Planners must be able to express their intentions in a normalized, canonical fashion that can be understood easily by the workers. The description of assembly operations is comparatively simple. While huge efforts were spent in training writers for the Caterpillar Fundamental English, the INTERACT usage does not assume the necessity for any language training at all. The reason for this lies in the user interface that will be adopted, which does not allow the planner to leave the language. In composing an assembly task from parts, the CNL description emerges. The CNL expressions on the one side and the actions, parts, tools etc. on the other are in a bijective relationship. By using the CNL, the terminology is at the same time unified across the company, as the CNL forces writers to use the same term for an item, and the same phrase for an action.

With acceptable effort, these CNLs can be transposed to other natural languages, which is, however, not part of the project INTERACT, but certainly within the space of necessities for the transnationally active pilot case partners Daimler and Electrolux.

4. Baseline and Results Assessment

As the previous chapter gave a description on how end users work with digital human models, this chapter has the purpose of describing the performance of the status quo digital human modelling software EMA (editor for human work activities). EMA will be used as a baseline for the measurement of the performance of the software prototype, which will be developed in INTERACT. Therefore, this chapter will give a brief impression of the features and work flow of EMA. To measure the performance of the developed prototype, parameters of performance will be defined. These parameters will be measured for the INTERACT prototype and the EMA version of January 2014. At this point it is important to state, that the performance will be evaluated in the frame of the defined use and pilot cases. Therewith, the measured performance only compares the performance for these cases and their explicit features and characteristics.

4.1. EMA

4.1.1. Introduction

The EMA software is a holistic 3D planning tool for the simulation of human work activities in industrial production. A key concept of EMA is the approach of self-initiated motion generation by the human model, which decreases the effort for users in simulation preparation and tries to increase the validity of simulation results in terms of realistic motion trajectories and biomechanical correctness. This is primarily done by changing the traditional method of motion simulation using a step-by-step animation procedure into a task- and object-oriented approach with parameterized human movements that are calculated with generic algorithms. EMA is already capable of reproducing most of common work-related activities. Key features of the EMA software are the implemented assessment functions, using 'state-of-the-art' methods like MTM (Methods Time Measurement) for time analysis and EAWS (Ergonomic Assessment Worksheet) for ergonomics risk evaluation

4.1.2. Creating a scene

The first step of every simulation of human work activities (hereinafter 'simulation') is the creation of a virtual working environment (work place or scene). EMA uses different types of geometry data formats to produce elements for a scene:

- Geometric primitives

  → EMA intern objects like cubes, tables, racks, cylinders, and markers which can be varied in their dimensions at the point of creation or adapted later in a refining process.

- Collada format (.dae)

  → open source CAD format, which is based on xml language and was developed as exchange format for different CAD tools.

- .jt format

→ Cad format, which is related to SIEMENS. On 2012 December, JT has been officially published as ISO 14306:2012. EMA supports .jt-files up version 8.x.

The process of layout definition is similar to current 3D simulation standards. The organization and definition of positions and orientations can be done by alphanumerical input or interactive 3D manipulation via 3D window. The 'objects" workbench also includes features like the creation and manipulation of object-structures (hierarchy), object mass, digital human models of different percentiles, and the (in-)visibility of objects.

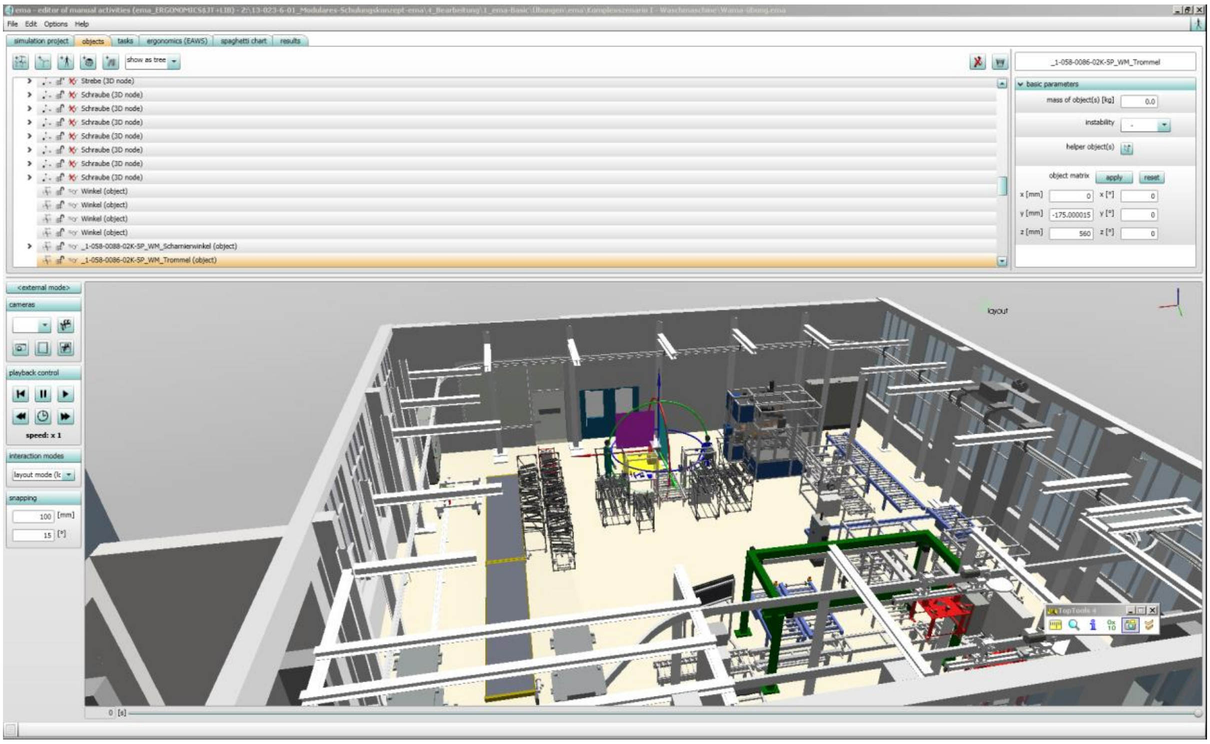

Figure 2: EMA workbench

4.1.3. Task/movement definition

The movement or behavior definition in EMA follows its approach of a task-oriented self-initiative motion generation. The description of the manual process is realized by the combination of different "tasks", which are compiled in the "task library" (a). The tasks are defined in accordance to the MTM-method and represent most common tasks in work activities like 'pick object'. 'place object', 'walk', 'use tool', etc.. Single tasks are put into each virtual worker's timeline (b) by drag and drop.

For example:

Task description:

"Assemble the rear mirror at the door with two screws"

Timeline:

Worker 1	pick mirror	pick screwd	place mirror	pick 2 scre	place	place :	use screwdriver 1	use screwdriver 2
time [s]	0	1.25	2.5	3.75	5	6.25	7.5	8.75	10	11.25	12.5	13.75	15	16.25

Figure 3: EMA task description in a timeline

As shown in the figure above, in EMA the assembly task is defined by eight single tasks, which include picking the mirror, the screws, and the screwdriver. After that mirror and screws have to be placed and the screwdriver is subsequently used to mount the screws. Walking paths are created automatically for each task.

Every task needs the definition of different obligatory parameters by the user. 'Picking' for example needs at least the information, which object has to be picked by the DHM with which hand(s) (c). Next to this there are optional parameters for every task. Often used optional parameters are forced body postures, lock leg movement or processing time.

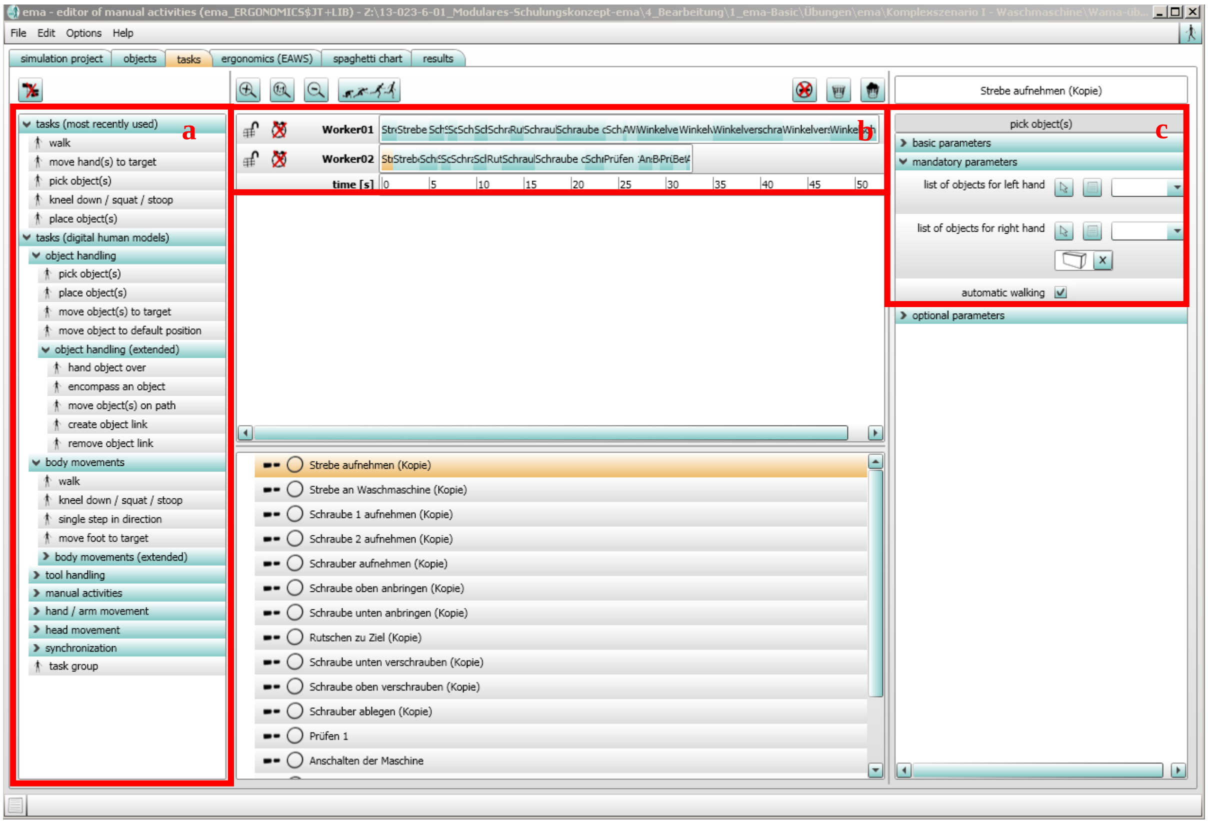

Figure 4: here EMA 'Tasks' workbench. a. task library, b. timeline, c. task parameter

4.1.4. Assessment tools

EMA offers different assessment tools for time related and ergonomic assessment of the simulation process.

The ergonomic assessment workbench is based on EAWS (Ergonomic Assessment WorkSheet) (Schaub et al. 2012). EAWS is an international established assessment tool, which focuses on the holistic work load within manual tasks. The main parameters for the analysis are body postures, forces, loads and the frequency respectively the duration. Additionally extra points can be added for special difficult working conditions like impulses, hot objects, or vibrations. The result of an EAWS analysis divides into the three categories green (no need for action), yellow (intermediate risk), and red (immediate need for modification of the work place).

The second assessment tool is the so called spaghetti diagram, which allows analysis of walking paths. The analysis includes distances, times and the relative time at several work stations.

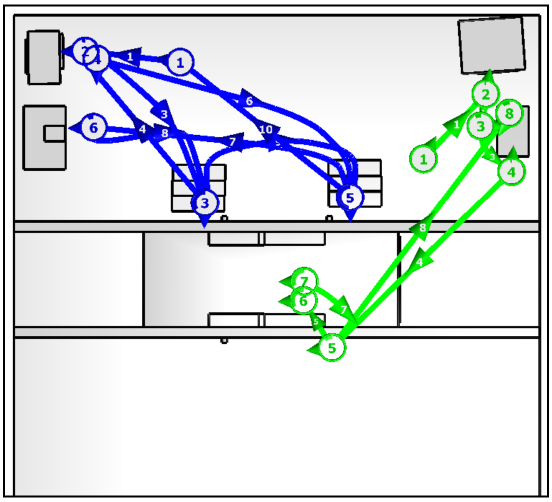

Figure 5: EMA spaghetti diagram with two workers

Next to these assessment tools, there is a time and added value based assessment. In these tools the user gets basic information about time, distances and added value for every task. The results are presented in a numerical and graphical manner.

4.2. Parameters & Methods for software evaluation

The idea behind a baseline definition is a reliable and explicit description of the status quo. To reach that goal different aspects have to be taken in mind. First of all it is necessary to define parameters and the corresponding methods for measuring them. The parameters are derived from the requirement list on one hand of and on the other hand from the pilot cases, which define the frame of the aspired performance and features of the INTERACT prototype.

Performance parameters

The first category of evaluation is the performance. Performance parameters in this case are technical parameters in the areas of graphics and calculation time.

Quality of Results

The quality of the simulation results, as one of the main goals for development in INTERACT, is the most difficult to determine. Since the quality of a motion in terms of style and the proximity to human like behavior is not exclusively objective, but underlies the subjective impression of the observer. Nonetheless it is necessary to define objective measurable parameters next to empirical user ratings, gathered from questionnaires. These measurable parameters are defined in chapter 4.4.

Usability

Usability is an important aspect of the quality of software. The three key aspects of usability are effectiveness, efficiency and satisfaction. While effectiveness and efficiency can be measured by certain parameters, satisfaction is difficult to determine. Beside this, one should consider, that the goal of INTERACT is the development of a prototype and not a marked-ready software product and within that the usability is not a key goal.

Therefore, the assessment of the usability will be limited to a comparison of the methods, movement definition, motion refinement and the process of motion capturing. Usability related parameters like response time are evaluated in the performance chapter and should not be evaluated twice. Especially the motion definition and interactive changing is an important requirement by the industrial partners and a major subject in the use cases. Within these issues it should be considered, that all potential user groups have to be evaluated, considering their different level of expertise.

Features

The last evaluated criteria is a list of features, which is generated from the list of requirements for the INTERACT prototype. The Baseline software EMA and the INTERACT prototype will be tested against this list, whether they include the different features or not.

The vision of the project is to provide means to automatically generate a model for the manual operations. Indicatively, with the software Delmia V5, the time to generate a 3D simulation model for one station was one to two weeks for a user who has received trained in Delmia V5 but not an expert in the Human module.

With the software EMA by imk automotive, modelling time could be reduced to 2 days with 2 expert users from imk automotive. However, the resulting models are less realistic – especially considering hand movements. For both Delmia V5 and EMA V5, the computer needs around 20-30 GB of RAM to process all the data.

4.3. Success criteria

In the table below the list of criteria that will be used for accessing the success of the 3D human simulation generation and interaction are presented. The methods to assess those criteria are also discussed.

No	Success Criterion	Type	Measures	Target Objective
1	Time spent to develop/build a digital human simulation model for work activities (assembly tasks, materials handling) when developing a	Usability	Modelling time spent per simulated time	50% - 70% reduction compared to current industrial practice (based on Delmia V5 Human Task

	simulation model "from scratch" (e.g. in the occasion for process planning of a new product or product variant) and get a first verified DHM based simulation of the process (1st simulation run).			Simulation) which is ~ 1 person week per simulation minute AND At least as good as EMA which is ~ 2-4 person days per simulation min
2	Time required for manually updating a 3D human simulation model that improves the process design following or in parallel to a prototype production phase.	Usability	Modelling time spent per simulated time.	At least as good as EMA which id 15-30 minutes per simulation minute
3	Integration of Motion Captured data to 3D human simulation models during collaborative sessions with limited time constraints	Usability	Time required updating a 3D human simulation with Motion Captured data.	2-3 changes in the order of the worker tasks recorded during the pilot workshops AND 4-5 changes in the process parameters recorded during the pilot workshops
4	Alternative scenarios should be planned by workshop participants. The definition of user initiated scenarios that describe alternative process plans during on-line collaborative workshops with strict time limitations	Usability	Number of user initiated scenarios in on-line collaborative workshops with strict time limitations	2-3 user initiated scenario changes during process review workshops. Currently, no changes are possible in the simulation model due to the complexity to implement them.
5	Adequacy of 3D simulation for performing digital simulation analysis	Quality	Objective estimates based on several criteria (see chapter below). The objective assessment will be validated based on questionnaire for assembly verification workshop participants.	Should be at least as good as a DELMIA v5 approach and considerably better than EMA
6	Calculation time required to generate a new 3D human simulation.	Performance	Computation time required for the generation 1 sec of simulated time.	Maximum 5 times for calculating changes.

Table 2: Success criteria measurement

4.4. Assessing the adequacy of 3D human simulation models for process verification in the industry

Simulation models that are based on DHM are used for the verification of assembly processes in manufacturing industry. However, currently the adequacy of such models for the needs of process (such as assembly) verification can only be subjectively assessed by empirical user ratings, gathered from questionnaires. The purpose of this paragraph is to propose a framework that can objectively rate the adequacy of a DHM based simulation model for process verification purposes. This framework can be used to objectively compare the models generated by different DHM based simulation methods or tools or it can be used to support that the use of a simulation model is at least as valid as the use of a physical prototype that is built for the same purposes. An important factor that should be considered when rating the adequacy of simulation model is the role of the person that is interested in some verification aspect of an assembly process. Typical roles are ergonomist and task engineer (someone who assesses the performance).

The objectives is to implement those measures and their calculation method within INTERACT and validate them by comparing subjective assessment of field experts within INTERACT industrial partners.

No	Measure Name	Measure description and rationale	Calculation Method
1	Collisions (penetration greater than 5 mm)	Hypothesis: The more collisions exist during a simulation the less likely it is that this simulation is valid for validation and assessment of a process.	%of simulation time that is collision free
2	Simulation realism	Hypothesis: The less realistic a simulation looks like the less useful it is for validation and assessment of a process.	Rather complex measure is required here: • Minimum jitter or maximum smoothness in movement. • Use dynamics/physics to assess a simulation generated based on kinematics (e.g. center of DHM mass) (DeMagistris et al. 2013). • Body limbs profile (e.g. hand movements have a bell-shaped speed profile in straight reaching movements) (DeMagistris

			et al. 2013). • Head movement (e.g. looks at part when picking a part)
3	Spatiotemporal constraints satisfaction	Hypothesis: If one or more process constraints (e.g. pick tool located in x,y,z within a time period) are not satisfied during the DHM based simulation the less valid this simulation is for process verification purposes.	Check list: • All parts/tools described in the work tasks are picked and placed correctly.
4	Process execution	Hypothesis: If a DHM based simulation of an assembly process contradicts the process description then the simulation is unusable for process verification.	Comparison (in %) of correctly simulated process sequence to planned process sequence.
5	Precision in scene/objects representation	Hypothesis: Real world items usually vary in terms of dimensions, placing in 3d space etc. from the CAD models that were created during the design stage. A measurement of these deviations may be needed to provide an index of how well the model represents the actual scene that it simulates.	• Geometric variations of each object • Placement deviation of all objects in all 6 DOFs
6	Completeness	Hypothesis: If a DHM based approach for process verification cannot simulate all the process steps then this simulation is less usable for process verification.	Percentage (%) of process steps that have been simulated by a DHM approach and are clearly visible.

Table 3: Measures for adequacy of 3D human simulation models for process verification in the industry

5. REQUIREMENTS ANALYSIS

5.1. Introduction

Manual assembly simulations can significantly differ from the resulting assembly line operations they depict. These differences, however, are not yet methodically evaluated and used in such a way that could feed knowledge back to the simulation environments. **INTERACT** will utilize sensor data coming from assembly line operations and their difference with the planned, simulated ones, in order to achieve:

- Improvement of the realism of the digital models of manual assembly operations, as well as increased confidence in the simulation results.
- Improvement of the performance of the planned assembly processes (for example in terms of ergonomics, throughput and utilization).
- Reduction of the time required to build digital models of assembly processes.

5.2. Vision and Key Features

Here we detail some important features that are required to fulfil user needs in their work as described in the previous chapter.

5.2.1. 3D DHM level

<u>Realistic movements</u>

The movements should be simulated on a realistic basis, corresponding to human normal behaviour. For instance, simulation of picking operation must be realistic time wise. Motion Captured data taking with human subjects shall be combined with movement synthesis algorithms to model the large range of movements to be studied during the INTERACT project.

Using collision detection, DHM shall support obstacle avoidance during complete or partial body movement by suggesting realistic movement to avoid the obstacle(s). DHM movements must be continuous and smooth

<u>Motion synthesis</u>

DHM shall support the definition of walk paths and their related postures. The motion synthesis method should be extensible, to allow simulation of new movements. A clear methodology should be given to update the motion synthesis capabilities with new motions (e.g. through Motion Capture.). This is mandatory since the movements that will be studied during the project will cover only a small part of the users' needs. Finally, multiple workers shall be possible to be simulated in sequential operations. Parallel operations must be simulated, e. g. picking and walking, walking and turning

Introduction of forces

Human motion simulation model shall be able to simulate the presence of forces. The physical aspects of the objects shall be taken into account. For instance, forces and their impact on workers when performing certain activities (e.g. clipsing) should be taken into account.

Task variability

Modification of anthropometrical characteristics shall have effect on postures and movements. Definition of postures and movements shall also depend on environmental, task, spatial and temporal constraints.

Ergonomic Assessment

The solution has to evaluate ergonomic aspects related to postures and movements.

This evaluation will be based on conventional methods like EAWS, NIOSH, reachability and ergonomic landscapes. Ergonomic assessment should be done on a dynamic simulation and not just static postures basis.

5.2.2. Design engineer/process planner expert level

Model generation and interaction

An initial automatically generated human simulation model from textual process description. The user should be able to modify several aspects of the 3D DHM simulation model.

Usability in defining alternative movements

Definition of alternative task scenarios and movements shall be independent from the experience of the operator. The user should able to define alternative task execution scenarios in very short time.

5.2.3. Ergonomics expert level

INTERACT simulation should be possible be integrated to Ergonomics methods to perform ergonomics analysis on the simulated motion.

5.2.4. Software integration

INTERACT system should realize data retrieval from CAx systems via JT for geometric data and structured interfaces (e.g. XML based) for alpha-numeric data.

5.3. DHM motion generation and interaction system requirements

5.3.1. Elementary motions to be simulated

In this paragraph the elementary motions that should be simulated and synthesized by the INTERACT simulation module to be developed in WP2 “Best-fit simulation” are described. The elementary motions have been derived by analyzing the three pilot cases of the project. The elementary movements have categorized into the following categories:

- **Pick (Grasp)** is the motion used when the purpose is to gain control of one or more objects. In most case a pick movement is followed by a **move.** It attached hand(s) to object
- **Release** is the relinquishing of control of an object by the hand or fingers. Detach hand from object.
- **Insert** is the placement of a component inside another
- **Attach (or engage)** is to connect objects.
- **Detach (or disengage)** is the basic element used to break contact between one object and another. Disconnect objects
- **Move object** the predominant purpose is to transport an object to a destination.
- **Touch** object with the end-effector.
- **Turn** is a movement that rotates the hand, either empty or loaded. The movement rotates the hand, wrist, and forearm about the long axis of the forearm.
- **Look at** changes the head orientation.
- **Use Tool** is a movement for performing operations with tools.
- **Body Position (Motion)** are motions of the leg-foot, horizontal torso motions, and vertical torso motions. Values include stand, sit (straight/slumped), squat, kneel (one/twoknees), lay (prone/supine/side), crawl, bend and walk.

No.	Movement Category	Description	Elementary movement	Middle Console	Rear-light	Ware-house
1	Pick (Grasp)	Attach hand(s) to object	Pick-up using right/left hand or both	×	×	×
2	Pick (Grasp)	Attach hand(s) to object	Transfer (control transfer grasp from one hand to other)	×		
3	Pick (Grasp)	Attach hand(s) to object.	Regrasp (Change grasp without relinquishing control)	×		
4	Pick (Grasp)	Attach hand(s) to object	Contact Sliding, or Hook Grasp			
5	Release	Detach hand from object	Release right/left hand or both	×	×	×
6	Insert	Place component inside another	One hand moving towards the other, both holding components	×	×	
7	Attach	Connect objects	Attach/Connect/Engag e objects	×	×	
8	Detach	Disconnect objects	Disengage	×		
9	Move	In Move object, the predominant purpose is	Push/pull object	×		×

	object	to transport an object to a destination.	(extend / retract arms)			
10	Move object	In Move object, the predominant purpose is to transport an object to a destination.	Carry (move body to change position while holding object)	×		×
11	Move object	In Move object, the predominant purpose is to transport an object to a destination.	Press/Lift (move object down/up)	×		×
12	Touch	Touch object with the end-effector	Apply pressure with finger			
13	Turn	Turn is a movement that rotates the hand, either empty or loaded.	The movement rotates the hand, wrist, and forearm about the long axis of the forearm (left/right).	×	×	
14	Look at	Change head orientation	Turn head to look around		×	×
15	Use Tool	Use battery tool	Loosen/Tighten nut	×	×	
16	Use Tool	Use cordless screwdriver/tool	Bolt-Connect/Disconnect		×	
17	Use Tool	Rivet gun	Hammer rivets		×	
18	Touch	Use a machine's controls	Press button (left/right) hand			×
19	Body Position	Vertical Motion	Kneel (one leg or both)			
20	Body Position	Vertical Motion	Bent forward			
21	Body Position	Horizontal Motion	Side step	×		
22	Body Position	Horizontal Motion	Walk unobstructed and without carrying loads	×	×	×

Table 4: List of motions to be simulated in INTERACT

5.3.2. Derivation of a sequence of elementary motions from planning texts

The definition of a sequence of motion elements that execute the task will be achieved through CNL that will map the description of tasks to motion elements. Assembly descriptions based on a Controlled Natural Language (CNL) have a significant advantage over those formulated without restrictions – they can easily and unambiguously be parsed, processed and generated. The CNL system enforces the use of controlled language and therefore makes it possible to automatically process and analyze assembly descriptions.

The CNL descriptions of assembly activities come at different grain sizes. In any case, an assembly shall be represented by a sequence of CNL expressions in their temporal order. Each CNL expression is analyzed (see below). The analysis consists of linguistic analysis on the one hand and enrichment with parameter values on the other.[1] For ease of reference let us call the formal language, in which analyses are represented, SD (for Semantic Descriptions).

Each SD expression can be mapped onto a sequence of motion elements that are used to visualize the intended meaning. More formally, *a homomorphism from SD expressions onto sequences of motion elements shall exist*.

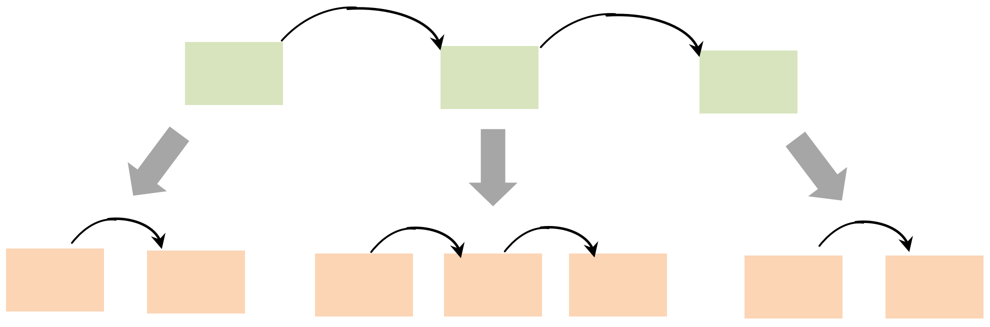

Figure 6: Homomorphic Mapping (grey) of SD Expressions (green) Onto (Sequences of) Motion Elements (orange)

Figure 6 depicts a situation in which for each of the SD expressions a sequence of motion elements has been found. The borders between the adjacent sequences need to be merged, unless mergers from the past can be reused. The merging results depend on the supplied parameter settings; they will be stored for future reuse.

The merging is context-dependent. Therefore the interface from SD to the selection of motion elements consists of a sequence of two SD expressions, namely the current one to be mapped, and the subsequent one, which the current one must merge with. This can be seen like a window shifted over the sequence of events, when the material "left behind" is already visualized, and the material "ahead" consists of CNL statements.

Requirement	Description
Automatic derivation of a sequence of elementary motions from planning text.	The INTERACT system should be able to derive the sequence of elementary motions (e.g. picking, walking, turning etc.) from initial textual description plus dynamic and static role filler properties as constraints over motion sequences.

Table 5: Requirements for derivation of a sequence of motions

[1] To be specified. For instance: 3D location, weight, grasp points.

5.3.3. Motion constraints generation

The INTERACT system should be able to define the motion constraints (e.g. what part to pick, where to place it, using left or right hand etc.) by utilizing data coming from CAD, CAPP system regarding the process that should be simulated.

Some CNL expressions are underspecified with regard to the properties of the participating elements. Each element (e.g. "cordless screw driver", or "middle console") has parameters such as weight, grasp points etc. *The values of these parameters must be available, with a unique index pointing from the ontology to the data.*

Similarly, some CNL expressions are underspecified with regard to details of the activities. For instance, the activity of picking up screws can be carried out by picking one screw at a time, or all screws at once. Screws can be carried in one hand, in both hands, or in the trouser pocket (other manners possible). *The CNL must explicitly mention any non-retrievable details of movements that pertain to the selection of motion elements.*

Motion synthesis should take into account the environment in the sense that collisions with object in the environment and the animations of the avatar are avoided. In general, collision avoidance would need motion planning with a path planning approach that computes collision free movements for the avatar taking into account all individual joints the avatar might have. However, for an avatar with a high number of joints such an approach is computational expensive. Depending on what kinds of movements are needed more efficient solutions are possible. If for example the avatar needs to walk from one position to another in an environment which is not crowded with obstacles, it is possible to compute a navigation mash which consists of trajectories which allows the avatar to move without worrying about collisions if its centre of mass is following the trajectory accurately enough. To achieve this the avatar is usually put into a bounding box or into a cylinder and computes paths which allows this bounding box or cylinder to move without collision from one position to another one. While moving the avatar is then allowed to act freely in this bounding box or cylinder. The situation gets more complex in case the environment contains moving objects itself. However, if the movements of these objects are not too complex they can be taken into account.

Apart from the constraints that are inferred by analysing the environment the user should also be able to modify or explicitly define constraints (e.g. define a specific point in a walk path).

Requirement	Description
Automatic inferring of motion constraints from	The INTERACT system should be able to

product, process and resource data and a-priori knowledge	automatically define the motion constraints by utilizing data coming from CAD, CAPP, work task information including descriptions, relevant parts, worker assignment, worker position.
Collision free DHM walks	The motion planning subsystem should generate movements of the DHM that are collision free.
Explicit definition of a constraint in the 3D space	The user should be able to explicitly define new constraints in a motion or to explicitly change an inferred constraint.

Table 6: Motion constraints generation requirements.

5.3.4. Motion synthesis

The INTERACT human motion simulation system should be able to smoothly *combine primitive human motion in order to generate new motions*. This will allow the concatenation of primitive movements to form a rich repertoire of human activities. Moreover, *the motion synthesis method should be extensible, to allow simulation of new movements*. A clear methodology should be given to update the motion synthesis capabilities with new motions (e.g. through Motion Capture.). This is mandatory since the movements that will be studied during the project will cover only a small part of the users' needs. Motion synthesis capability will provide the backbone to enable the user to accurately and interactively control a DHM by simply issuing high-level control commands such as “walking to reach a point and “picking up the object at”.

Moreover, it should be able to *generate and simulate parallel operations, e. g. picking and walking, walking and turning*.

The requirements for motion synthesis are listed in the following table:

Requirement	Description
Combine human motions in order to generate new motions	The motion generation system should be possible to combine several motions and generate a big repertoire of motions.
Motion adaptation to new constraints	The INTERACT motion generation sub-system should be able to adapt a motion to new motion constraints. • Change the DHM • Change the environment • Change both DHM and the environment
Motion generation capability should be extensible to a numerous types of motions	The motion generation system should be possible to be expanded and include other types of

	motions that may not be included in the initial list defined by the project case studies.
Generation and simulation of parallel operations of one worker	It should be possible to generate motions that execute parallel operations e. g. picking and walking, walking and turning.

Table 7: Motion synthesis requirements

5.3.5. Model interaction

5.3.5.1. CNL based interaction

The system described in (Manns and Arteaga, 2013) enables the planner to express assembly activities in CNL. Based on the activity, the system presents to the planner a template with placeholders for its possible roles. Some roles are optional, others are obligatory. For each role, the system also presents a set of reasonable filler parts. These filler parts are extracted from various external data sources. The planner selects suitable fillers, and the CNL text is generated, as planning proceeds. By virtue of the CNL, the planner cannot accidentally generate uncontrolled text. Both templates and filler parts are available in several languages, which allows for the automatic translation of the assembly activity descriptions into any other supported language. The current working hypothesis is that a similar interface is suitable for INTERACT as well. By and large this depends on the complexity of the CNL required.

5.3.5.2. Sensor based interaction

The INTERACT simulation model should be editable though the sensor system. A user should be able to execute a task or a portion of a task (i.e. some steps) within a motion capture area and the captured motion should be used to update/edit the DHM based motion simulation. For example an engineer may want to assess a 'what-if' scenario in which a different tool type (than the planned one) is used and the tool is located in a different location than the one planned. If the new tool type is available in the motion capture area the user may execute and capture the portion of the whole task that is related to the use of the new tool type (and new tool location). Then the INTERACT system should be able to update the originally planned, simulated motion with key-aspects (e.g. new tool location, new tool type, probably new working posture using the new tool) of the captured motion. The update should be possible through utilizing the motion synthesis and generation functionality. Further, details on how the INTERACT sensor system can be used to provide input to motion synthesis is given in INTERACT D1.2.1 chapter 5.1.1 and 5.1.2.

5.3.5.3. Change order of work tasks

The INTERACT simulation model should be editable by modifying (aka add, remove or change the order) of work task. A user should be able to change the execution order of work tasks and the INTERACT simulation system should be able to simulate the new work task execution order or to report exceptions and inconsistencies.

Requirement	Description
CNL based interaction	The user may modify terms in CNL descriptions.
Sensor based interaction	The user may initiate some Motion Capture session (using sensor technology to be defined in INTERACT WP4). The new captured motion, which corresponds to some specific task, can be used to update/edit the DHM based motion simulation.
Change order of work tasks	The user should be able to change the order of work tasks and this should be depicted in the simulated motion.

Table 8: Requirements for interacting with the DHM based process model.

5.3.6. Motion simulation / animation

The INTERACT system apart from motion synthesis and generation should be able to simulate/animate a generated motion. The INTERACT simulation subsystem should implement the following requirements:

Requirement	Description
DHM motion simulation/animation	The INTERACT simulation subsystem should be able to simulate a DHM motion
Scene objects (not only DHM) should able to change during simulation	Objects in the scene (e.g. parts, tools) should move during simulation. • Objects moving along with DHM (e.g. worker carrying a part) • Objects moving on the occurrence of some event (e.g. worker presses a button and a part rotates) • Object moving when the object that it is attached to is moving (e.g. part on table moves when the table is moving)
Work step recognition during 3D simulation	During simulation it should be possible to recognize (through annotation) the work steps executed by the DHM.

Table 9: Motion simulation/animation requirements

5.3.7. Ergonomics assessment

The INTERACT system should be able to provide ergonomic assessment of existing DHM simulations. It should provide ergonomic assessment functionality for the EAWS, NIOSH and OCRA standards. More details on the ergonomics assessment requirement are provided in the Ergonomic App in INTERACT deliverable D1.3.1.

5.3.8. Non-functional requirements

In terms of system performance and quality, several important factors are relevant for the motion generation and subsystems of the INTERACT system. See the following table for a list of non-functional requirements the system has to implement.

Requirement	Description
Motion must be smooth	The generated motion should be smooth without jerkiness or sudden locomotion or body limbs.
Realistic human motion simulation	Human motion must be realistic incl. acceleration and deceleration behavior
DHM walk paths must be continuous and smooth	There should be no human body sudden locomotion. The walking pattern (e.g. make a side step after having walked forward) should change smoothly.
DHM simulation must be changeable on-the-fly	The simulation model should be editable and re-generated on the fly so as it may support on-line collaborative sessions.

Table 10: Non-functional requirements

6. CONCLUSIONS

The primary conclusions/results include the following:

- The main result of this deliverable is the list of requirements and key features for the INTERACT motion simulation developments to take place in WP2 “Best-fit simulation of manual assembly using sensor data”.
- The analysis of the state of the art has indicated that there is a high potential in using the principles of the morphable graphs approach for a baseline in DHM simulation.
- The list of success criteria will be used in WP 6 “Industrial Pilot Cases, Demonstration and System Validation” for assessing the performance of INTERACT motion generation and synthesis approach.

The requirements defined in this document will serve as an input to the RTD tasks of WP2 “Best-fit simulation of manual assembly using sensor data”.

7. Glossary

DHM	Digital Human Modelling
PLM	Product Lifecycle Management
MMT	Material Management Team
VMS	Virtual Manufacturing Software
RULA	Rapid Upper Limb Assessment
MOST	Maynard Operation Sequence Technique
AAWS	Automotive Assembly Worksheet
CAPP	Computer Aided Process Planning
CAD	Computer Aided Design
C-values	C-Values are a Daimler in-house system that has been developed from MTM. Objectives are reduction of analysis time and application throughout the planning phase.
eHPV	Engineered Hours Per Vehicle
MV	Manufacturing Variable

8. References

1. Michalos, G., Makris, S., Papakostas, N., Mourtzis, D., Chryssolouris, G.: Automotive assembly technologies review: challenges and outlook for a flexible and adaptive approach. CIRP Journal of Manufacturing Science and Technology 2(2), 81–91 (2010)

2. Chryssolouris, G., Manufacturing Systems: Theory and Practice, 2nd Edition, Springer-Verlag, New York, New York, (2006)

3. Manns and Arteaga 2013, Automated DHM Modeling for Integrated Alpha-Numeric and Geometric Assembly Planning, M. Abramovici and R. Stark (Eds.): Smart Product Engineering, LNPE, DOI: 10.1007/978-3-642-30817-8_32, pp. 325–334

4. Siemens 2014, http://www.plm.automation.siemens.com/en_us/products/tecnomatix/assembly_planning/jack/

5. Dassault Systemes 2014, http://www.3ds.com/products-services/delmia/

6. K. Alexopoulos, D. Mavrikios, G. Chryssolouris, "ErgoToolkit: an ergonomic analysis tool in a virtual manufacturing environment", International Journal of Computer Integrated Manufacturing Vol.26, No.5, pp.440-452 (2013)

7. Härtel, T. ; Keil, A.; Hoffmeyer, A.; Toledo Munoz, B.: Capturing and Assessment of Human Motion during Manual Assembly Operation, First International Symposium on Digital Human Modeling, Conference Proceedings, June 14-16 2011, Lyon, France.

8. Fritzsche, L., Jendrusch, R., Leidholdt, W., Bauer, S., Jäckel, T., Pirger, A.: Introducing EMA (Editor for Manual Work Activities) – A New Tool for Enhancing Accuracy and Efficiency of Human Simulations in Digital Production Planning. In: Duffy, V.G. (ed.) ICDHM 2011. LNCS, vol. 6777, pp. 272–281. Springer, Heidelberg (2011)

9. Gläser, D.; Fritzsche, L.; Bauer, S.; Leidholdt, W., The quest to validated human motion for digital ergonomic assessment, AHFE 2014 – conference Proceedings, Krakow (2014)

10. Schaub, K., Caragnano, G., Britzke, B., Bruder, R. (2012): The European Assembly Worksheet. Theoretical Issues in Ergonomics Science, 27 April, No. 1.

11. Giovanni De Magistris,,, Alain Micaelli,,, Jonathan Savin…, Clarisse Gaudez…, Jacques Marsot, Dynamic Digital Human Model for ergonomic assessment based on human-like behaviour and requiring a reduced set of data for a simulation, 2013 DIGITAL HUMAN MODELING SYMPOSIUM.

12. Mavrikios, D., Pappas, M., Kotsonis, M., Karabatsou, V., Chryssolouris, G., "Digital Humans for Virtual Assembly Evaluation", Digital Human Modeling, Duffy V.D. (ed), Volume 4561, pp. 939-948, Springer-Verlag (2007)

13. Pappas, M., Karabatsou, V., Mavrikios, D., Chryssolouris, G., "Ergonomic evaluation of virtual assembly tasks", Digital Enterprise Technology: Perspectives and Future Challenges, P. Cunha, P. Maropoulos (eds), Session 5, pp. 511-518, Springer-Verlag (2007)

14. Chryssolouris, G., V. Karabatsou and G. Kapetanaki, "Virtual Reality and human simulation for manufacturing", Proceedings of the 34th International CIRP Seminar on Manufacturing Systems, Athens, Greece, (May 2001), pp. 393-398.

15. Park, W., Chaffin, D.B. and Martin, B.J., Toward memory-based human motion simulation: development and validation of a motion modification algorithm. IEEE Trans. Systems, Man, Cybernetics, Part A: Systems and Humans, 2004, 34, 376–386.

16. Bruderlin, A. and Williams, L., Motion signal processing. Proceedings of SIGGRAPH, Los Angeles, California, 1995, pp. 97–104.

17. Witkin, A. and Popovic, Z., Motion warping. Proceedings of SIGGRAPH, Los Angeles, California, 1995, pp. 105–108.

18. Gleicher, M., Retargeting motion to new characters. Proceeding of ACM SIGGRAPH Conference, 1998, pp. 33–42.

19. Yang, J., R. T. Marler, H. Kim, J. Arora, and K. Abdel-Malek, “Multi-objective optimization for upper body posture prediction”, Proceedings of the 10th Multidisciplinary Analysis and Optimization Conference (AIAA/ISSMO), Albany, N.Y., American Institute of Aeronautics and Astronautics (AIAA), 2004.

20. Kovar, L., Gleicher, M., and Pighin, F. 2002. Motion Graphs. In ACM Transactions on Graphics. 21(3):473–482.

21. Safonova, A., and Hodgins, J. K. 2007. Construction and optimal search of interpolated motion graphs. In ACM Transactions on Graphics. 26(3).

22. Heck, R. and Gleicher, M. 2007. Parametric motion graphs. In 2007 ACM Symposium on Interactive 3D Graphics.

23. Min,J., Chai, J. Motion graphs++: a compact generative model for semantic motion analysis and synthesis. ACM Trans. Graph.31(6) 2012.

24. Demirel O. and Duffy V., 2007. Applications of Digital Human Modeling in Industry. In: V.G. Duffy (Ed.), Digital Human Modeling, HCII 2007, LNCS 4561, 824–832.

25. Rhen, I.M., Gyllensvärd, D., Hanson, L. and Högberg, D., 2011a. Time dependent exposure analysis and risk assessment of a manikin’s wrist movements. Proceedings of DHM 2011, First International Symposium on Digital Human Modeling, France, ISBN 978-2-9539515-0-9.

26. Rhen, I.M., Hanson, L. and Högberg, D., 2011b. Risk exposure assessment of dynamic wrist motions of a digital human model. Proceedings of the 43rd annual Nordic Ergonomics Society Conference, Oulu, Finland, September 2011, ISBN 978-951-42-9541-6.

27. Ma, L., Zhang, W., Fu, H., Guo, Y., Chablat, D., Bennis, F., Sawanoi, A., and Fugiwara, N., 2010. A Framework for Interactive Work Design Based on Motion Tracking, Simulation, and Analysis. Human Factors and Ergonomics in Manufacturing & Service Industries, 20(4) 339–352.

28. Winter, G., Schaub, K., and Landau, K., 2006. Stress screening procedure for the automotive industry: development and application of screening procedures in assembly and quality control. Occupational Ergonomics, 6, 107–120.

29. Wojcik, R., & Hoard, J. (1997). Controlled Languages in Industry. In R. Cole, J. Mariani, H. Uszkoreit, G. Varile, A. Zaenen, A. Zampolli et al. (eds.), Survey of the State of the Art in Human Language Technology, (pp. 238-239). Cambridge: Cambridge University Press. Online available at http://www.lt-world.org/hlt-survey/master.pdf

30. Funk, A., Tablan, V., Nontcheva, K., Cunningham, H., Davis, B. & Handschuh, S. (2007). CLOnE: Controlled Language for Ontology Editing. In K. Aberer et al., (eds.), The Semantic Web. 6th International Semantic Web Conference, 2nd Asian Semantic Web Conference, ISWC 2007 + ASWC 2007, Busan, Korea, November 11-15, 2007. Proceedings, Springer: Berlin, Heidelberg, pp. 142-155.

9. APPENDIX I: USER REQUIREMENTS CATALOGUE FOR DHM BASED MODEL SIMULATION

	Need	Category
1	An ergonomy landscape has to be derivable from a 3 D simulation scenarios	ergonomic assessment
2	Assembly operations must be able to blend into each other (no return to base pose)	quality of results
3	Assembly operations must be smooth	quality of results
4	Assembly sequence must not contradict itself	quality of results
5	Assessment functionality for space requirements for station as in 3D scene	assessment general
6	Collision avoidance accuracy < 5 mm	features
7	Comfortable work area for a worker must be visualizable	ergonomic assessment
8	Containers must be able to move with the car (be positionable in moving coordinate system)	features
10	DHM MV processes (incl. walking) must be realistic incl. acceleration and deceleration behavior	quality of results
11	DHM MV processes (incl. walking) must be realistically timed incl. acceleration and deceleration behavior	quality of results
12	DHM MV processes (incl. walking) must look realistic	quality of results
13	DHM simulation must be changeable within the workshop by each participant	usability
14	DHM walk paths must be collision free	quality of results
15	DHM walk paths must be continuous and smooth	quality of results
16	Each work step must be recognizable in the 3D simulation	quality of results
17	Ergonomic evaluation of pick operations from part carriers with different filling percentage	ergonomic assessment
18	Ergonomic evaluation: EAWS criteria	ergonomic assessment
19	Ergonomy landscapes have to be comparable for multiple scenarios	ergonomic assessment
20	Error handling if a planning text does not match the controlled natural language	usability
21	Interactive comparison of planned MTM-1 bundles to the ones derived from the simulation (maybe with an automated comparison tool that displays deviations)	assessment general
22	Interactive reachability analysis	ergonomic assessment

23	Interactive user selection of screw or clip	usability
24	Movement generation of a DHM so that the hand or tool reaches a selected tool or clip	quality of results
25	MTM 1 bundle scenarios must be comparable	assessment general
26	MTM 1 bundles (C-Values) have to be derivable from the simulation model	assessment general
27	Multiple workers must be simulated in sequential operations	features
28	Parallel operations must be simulated, e. g. picking and walking, walking and turning	quality of results
29	Part carriers have to be movable in the 3D scene in the workshop	features
30	Part orientation operations must look realistic	quality of results
31	Picking operations must look realistic	quality of results
32	Planned MTM 1 bundles (C-Values) must be interactively changeable in the work shop	assessment general
33	Realistic simulation of one point picking (for larger parts) for assessment of feasibility	quality of results
34	DHM simulation scenarios must be comparable within the workshop	features
35	Simulation scenarios have to be associated with MTM 1 bundle scenarios and compared	assessment general
36	Simulation of part orientation must be realistic time wise	quality of results
37	Simulation of picking operation must be realistic time wise	quality of results
38	The visualisation must give feedback if there are walk way tasks that match the simulated walks	assessment general
39	The visualisation should propose addition, adaptation or elimination of inadequately planned walk paths	assessment general
40	Unrealistic worker poses must be recognizable or avoided (physical force)	quality of results
41	Visualization of view area of the DHM (part visibility) and automatic recognition of blind assembly situations	ergonomic assessment
42	Work process (eHPV and MV) times have to be realistic	quality of results
43	Work task sequence must be interactively changeable by workshop participants	usability
44	Works steps in the 3D simulation must correspond to work task descriptions	quality of results
45	(New) Item handling process definition	features
46	Clear visualization of hands representation and movements in item handling	quality of results
47	Enable manual modification of the proposed outcome of the item handling process definition	features

48	Trolley uploading process visualization	quality of results
49	Trolley design suggestion/modification	features
50	Warehouse container design	features
51	Warehouse shelves design	features
52	Picking process simulation (one item)	features
53	Picking process simulation for a complete sequence (all components per one trolley)	features
54	It should be possible to manual modify the outcome of the picking process sequence	features
55	Ergonomic assessment (NIOSH standard)	ergonomic assessment
56	During ergonomics assessment (NIOSH) there should be dynamic indications with red/green lights of the correctness of the operations	ergonomic assessment