Abstract

Both humans and robots have crucial advantages regarding industrial assembly processes. While robots ace at repetitive and monotonous assembly steps, humans are able to adapt flexibly to new situations and upcoming problems. Combining these advantages by means of direct human-robot cooperation seems to be interesting for producing companies but has not been realized yet. While the corresponding technologies are already available, appropriate safety standards to ensure occupational safety are missing and represent one of the main barriers for introducing direct human-robot cooperation. This paper describes the requirements for a workplace, where humans and robots jointly perform an assembly process without separation between their workspaces. The requirements are identified in line with an ergonomic workplace for different aged working persons, whereas the robot assists the human with the assembly process. The analysis considers technical, human-related, and normative requirements. Afterwards, an early implementation of the concept is presented based on a cognitively automated assembly system using a lightweight robot.

© 2015 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Peer-review under responsibility of AHFE Conference

Keywords: Human-robot cooperation; Ergonomic work conditions; Occupational safety; Cognitive automation

1. Introduction

The assembly process of today’s manufacturing companies can generally be decomposed into two categories of assembly steps. First, there are many assembly steps that can be performed autonomously in an effective and efficient manner using standardized industrial robots or handling devices. The corresponding automation
technologies have been developed rapidly in the last decades and can easily be used to build up an autonomous assembly line for simple products. However, the second category includes those tasks that cannot be fully automated mostly due to special sensorimotor skills that are necessary to succeed in these tasks [1, 2]. Wiring harnesses or seals are, for example, limp components that cannot be controlled properly by today’s automation techniques. Besides that, small lot sizes could also make investments in special automation and control technique uneconomically [3].

Therefore, the human operator will still be involved for a long time in the assembly process of many products, whether for performing certain assembly tasks or for supervising the automated assembly process. Combining the advantages of both, the human operator and robotic assembly systems, increases the performance of the overall system most efficiently [2, 4]. If products would be assembled cooperatively by the human and the robot, the robot could take over monotonous and strenuous tasks, in order to assure a constant quality and to improve the ergonomic work conditions. In addition, heavy weights or hazardous parts can be handled by the robot to relieve the human. As a consequence, the human is able to concentrate on the tasks that require his/her special skills, such as sensorimotor skills and creative problem solving.

However, current European laws and norms do not allow for a direct cooperation of the currently available industrial robots and the human. DIN EN ISO 10218-1 [5], for example, prescribes either a strict separation of the workspace of human and robot or at least an observed stop of the robot in case the human enters the collaboration space. Due to the high forces evoked by traditional robots, mechanical guards, such as safety fences, or electro-optical sensors ensure the occupational safety of the human as presented for various workplaces in [1]. However, such a strict separation of the workspaces prevents direct human–robot cooperation and, in particular, the simultaneous interaction of human and robot within the same space. Supporting actions such as adjusting the position of the work piece dynamically are not realizable while the operator processes the object at the same time.

In order to solve this dilemma, on the one hand new norms and laws are necessary. The draft standard ISO/TS 15066 [6] promises to fill this gap by specifying among others maximal action forces for collaborative robots. On the other hand, new technologies and control paradigms could help reducing the risk for the human to an acceptable level. Some of them are retrofittable for existing robots such as cameras, that are able to recognize the position of the human, or capacitive shells for the robot (e.g. [7], [8]), which predict and avoid collisions with the human. These technologies would circumvent the large barrier for companies of buying new robots. Opposed to standard industrial robots, lightweight robots represent a new generation of robots, which are restricted in force but are nevertheless able to carry large weights compared to their own weight. In addition, some of them are equipped with lots of sensors in order to measure forces raised by objects or the human in case of contact. Assuming that the conditions for human–robot cooperation were defined by new standards such lightweight robots would be co-worker for the human operator.

In this paper, the requirements resulting from the above challenges are identified for workplaces, where the human and robot can work together at the same time without any separation of the workspaces. The requirements are distinguished into functional, human-related and normative requirements, which are described in the following section. In addition, social and ethic aspects have to be considered including the degree of substitution of the human by the robot that is tolerated by humans and the degree of acceptance for the technical co-worker. These aspects will be examined separately, for instance, in terms of user studies. Based on the requirements described in this paper, an approach for a flexible assembly workplace for human–robot cooperation is presented.

2. Requirements for a collaborative workspace for human and robot

2.1. Method

The presented requirements analysis aims at designing a collaborative workspace, where both human and robot perform assembly or manufacturing tasks in a joint working area. We aim at abolishing the strict separation of the workspaces and the temporal alternation of the work process between human and robot. Human and robot should instead work cooperatively on the same product at the same time. In case of consecutive actions, components need to be handed over from the robot to the human and vice versa. Thereby, we likewise aim at direct interaction, i.e. one subject takes over the object directly from the other. However, work tasks related with dirt and dust are excluded as well as those requiring special clean conditions. The workplace is to be aligned for skilled manual workers of all
The automated control of the production process should be as flexible as possible in order to be competitive in the globalized world economy regarding an increasing variety in product range [9].

The requirements have been identified according to Franke’s approach [10] with respect to two dimensions. First, they are classified into technical and functional requirements, requirements related to the human, and normative requirements. In the second dimension, the requirements were gathered with respect to the product life phases manufacturing, distribution, utilization, and reuse. Thereby, the distribution phase is mainly considered as the transport of the workplace to a new operating place. The commercial sale is neglected at this point. Moreover, reuse is interpreted rather in terms of extendibility than decomposition and recycling of the workplace. Table 1 applies the product life cycle of Franke [10] to the specific case of the workplace for human-robot cooperation considered in this work. The requirements of the individual phases will be explained in the following subsections.

Table 1. Application of Franke’s product life cycle [10] to the case of a collaborative workspace.

| Product life cycle phase | Meaning in the context of the human-robot workspace |
|--------------------------|---------------------------------------------------|
| manufacturing            | planning and construction of the workplace for human-robot cooperation; comparison of available technologies |
|                          | preparation of the location of the workplace; order or manufacturing of components |
|                          | assembly of workplace; disassembly of workplace |
| distribution             | transport of the workplace to another operating place |
|                          | storage of the workplace in case of disuse for a longer time |
|                          | aspects for industrial sale |
| utilization              | operation, downtime; planned or unplanned downtimes in case of pauses or maintenance |
|                          | periodic maintenance of individual components |
|                          | unplanned repair of individual components |
| reuse                    | reuse of used components; rebuild of workplace; extension of workplace by new components |

2.2. Manufacturing phase

At the beginning of the manufacturing phase, the workplace has to be planned and designed. Technicians as well as non-technicians need to be involved herein, in order to identify and satisfy all requirements in light of the overall concept. The technical feasibility needs to be considered as well as higher level concepts, such as the possibilities for training the working person. Hence, it is advantageous to provide a digital model of the workplace. Using a CAD model all components can be planned in detail with respect to their space requirements with few efforts. In addition, the model serves as an abstract visualization of the workplace in the later product cycle. Various standards and norms provide help with designing an ergonomic workplace. DIN EN ISO 14738 [11] and VDI 3657 [12] specify ergonomic and anthropometric requirements with respect to the working person. As human and robot are asked to work cooperatively at the workplace, standards regarding the security of human-machine interaction have to be considered likewise. ISO 13854 [13], DIN EN ISO 13855 [14] and DIN EN ISO 13857 [15] state safety distances as well as details about the arrangement of safety devices, such as light curtains or emergency stops. Finally, EN 953 [16] and DIN EN ISO 14119 [17] describe the requirements of guards and their interlocking devices. Regarding human-robot cooperation, DIN EN ISO 10218-1 [5] lists the hazards of robotic workplaces and specifies constructional requirements. However, this norm was not established to introduce direct human-robot cooperation and there are no valid standards at the moment that allow designing such a safe workplace for human-robot cooperation. The new draft ISO/TS 15066 [6] might include further advices, when it is published, by specifying among others maximum forces for robots moving close to humans.
After having passed the concept of the workplace, the individual components have to be compared against the currently available technologies. The designers need to decide, which components can be purchased and which have to be developed by external experts. These decisions are also influenced by the qualifications that are available in the developer team. In order to maximize the flexibility and usability of the workplace, it should be possible to assemble and disassemble the workplace nondestructively and without any special tools. Using plug connections and simple screw connections, components or modules can easily be assembled and reorganized, if new requirements arise in the future. Moreover, the compatibility and integration of possibly existing components, such as sensor devices, need to be considered. The assembly process of the individual components should be dimensioned, so that it can be performed with only few persons without any exhaustion. Requiring more than three persons restricts the flexibility for reorganizing the workplace. The components and their installation position should be marked unambiguously and the assembly process should be assisted by a unique installation plan.

2.3. Distribution phase

The distribution phase includes the transport of the workplace (as the final “product”), if it is not manufactured and assembled at the final operating place or has to be moved to another place in the future in case the production of the company is reorganized. Therefore, it is advisable to design a modular workplace, which is decomposable and can thereby easily be transported without any stationary support system, such as indoor cranes. The dimensions of each component of the workplace have to satisfy local restrictions, for instance, if the component needs to be transported through “usual” inner doors. Labelling hazardous components and force application points can prevent injuries during the transport.

2.4. Utilization phase

Most of the requirements can be derived from the utilization phase. Regarding the robot, the main focus lies on its technical features and its capabilities in case of human-robot cooperation. The type of tasks that can be taken over by the robot depends among others on its accuracy and repeatability. In general, there is the choice between standard industrial robots or lightweight robots. While industrial robots usually need to be equipped with additional safety guards in order to be suitable for human-robot cooperation, lightweight robots often have integrated sensors but limited payloads. Moreover, the power supply may be a crucial decision criterion, if high voltage current for industrial robots is not available.

Regardless of the kind of robot, the dimensions of the workplace have to be chosen with respect to the dynamic forces of the robot in case of movement with highest possible payload as well as the additional forces induced by the human. The working height should be adjustable by the individual working person, so that persons of different heights are able to work ergonomically at the same workplace. Changing the working height also enables a switch between sitting and standing during the workday yielding a lower strain level according to the latest state of the art. The appliances, boxes and tools, which are necessary for the human to perform the assembly task, have to be aligned ergonomically regarding space within reach for both sitting and standing. The weight of heavy tools should be reduced by means of wire rope hoists and the work area should be illuminated flicker-free. Actuators and control panels are to be designed according to ergonomic standards and should provide sufficient information about the current system state and the state of cooperation. Hereby, it is particularly important to consider the points of time of activation and deactivation of the robot. However, detailed information should only be displayed on demand in order to not overburden the operator. For the case of emergency, the human must have the possibility to interrupt the movement of the robot. Therefore, emergency stops have to be provided at appropriate locations.

Direct human-robot cooperation induces novel challenges compared to standard industrial robotic applications. The physical integrity of the working person must not be endangered at any time. As already mentioned, appropriate standards and norms are being prepared but do not exist yet. The European machinery directive 2006/42/EG and the corresponding standards DIN EN ISO 12100, DIN EN ISO 10218, and DIN EN ISO 13849-1 describe detailed procedures for assessing the risk of a workplace and its individual components. In line with this, the control unit of the robot needs to satisfy the safety integrity level 3 and the performance level “d” as proposed by Missala. Accidental collisions between the human...
and the robot should certainly be avoided and the maximum force of the robot has to be restricted (see future standard ISO/TS 15066 [6] for further details). In addition, the carried objects and tools have to be secured in case of an energy outage and during downtime no accidental activation of the robot may occur [25]. Similarly, the system has to be secured against accidental misuse of the human.

Currently, DIN EN ISO 10218-1 [5] requires an immediate stop and an observed downtime while human and robot are in the same workspace. The robot is only allowed to be operated in manual mode with a maximum velocity of 250 mm/s. In future standards, more liberal approaches such as a reduction of the velocity dependent on the distance between the human and the robot [26] may be allowed as far as the corresponding control is failsafe enough. In order to adjust the velocity dynamically, a reliable location of the human is required, for example, by cameras or laser range scanner. The standards prEN/TS 62046[27], DIN EN ISO 13856-1[28], and DIN EN ISO 61496-1[29] describe different techniques for contact and contactless locating of the human. In order to indicate the working person the approach of the robot or an upcoming situation of cooperation, optical and acoustic signals can be installed [24]. Thereby, positive and negative meanings, i.e. acknowledgements and warnings, should easily be distinguishable. In addition, human-robot cooperation would benefit, if the robot reacts to voice and gesture signals of the human. However, the interpretation of these signals also has to satisfy the integrity level 3 [24].

Besides technical requirements, also cognitive-ergonomic requirements need to be considered. This includes the behavior of the automatic control program of the robot that should be in conformity to the operator’s expectations [30]. Designing the behavior transparently increases the trust in the technical system and makes the actions more predictable, which is desirable especially in case of human-robot cooperation. This can be achieved, for example, by selecting an appropriate assembly order [30] or by introducing anthropomorphic trajectories for the robot[31]. However, as faultlessness of software systems cannot be guaranteed, an automated system should hold detailed information available, in order to examine a possible incident.

For the cases of maintenance and repair, a detailed manual should be provided, which describes all components and their functionality. Nevertheless, the maintenance effort should be minimized. Relevant components have to be marked and accessible without any obstacles and collisions in an ergonomic manner. The consumption of wearing parts should be displayed and spare parts should be hold available. However, the likelihood of confusion with similar products must be minimized.

2.5. Reuse phase

In the context of this work, the reuse phase of the workplace is not interpreted as decomposing and recycling of the individual components. Rather, reuse means extendibility by future technologies. New assembly tasks may require a reorganization of the components of the workplace. In addition, new components such as new safety equipment may be installed in the future. In order to satisfy this flexibility, not only the hardware components but also the software systems should be based on standardized interfaces.

3. Design and implementation of a collaborative workspace

The aforementioned requirements have been implemented in an early prototype for collaborative assembly processes, which benefit from human-robot cooperation. Fig. 1 depicts the current state of the workplace using a Stromberg carburetor as product to be assembled cooperatively. Hereby, the human operator takes over the assembly of the parts that require extensive sensorimotor skills, such as the diaphragm and the return spring[32].
The other parts could be assembled autonomously by the robot using a gripper and a power screwdriver. Hence, the workplace enables both autonomous and partly automated assembly tasks and is not restricted to specific products (except by the physical limitations of the robot). The 6-DOF lightweight robot SCHUNK LWA 4P is mounted on the top of the joint workplace. The robot weighs 12.5 kg and has a maximum payload of up to 6 kg. Its repeatability amounts to ±0.15 mm and its space within reach up to 80 cm. For power supply the robot requires 24 V and up to 14 A. Hence, the robot can easily be moved to another operating place compared to stationary industrial robots or installed on a mobile platform. Due to its limited forces one great barrier of direct human-robot cooperation is abolished. In order to grasp and handle components, the two finger gripper SCHUNK PG+70 is used, which fits in seamlessly with the modular structure of the LWA. The workspace itself measures 156 cm x 106 cm and can be divided freely in different areas.

The control of the robot is based on the standardized protocol CANopen via CAN bus by means of the standardized profile CiA DS402:IEC61800-7-201. In order to control the robot, the popular open-source software Robot Operating System (ROS) [33] is used. ROS provides a flexible and modular framework for developing robotic applications across a wide variety of robot platforms. Numerous tools, libraries, and drivers are provided that help developing robotic applications with hardware abstraction.

Fig. 2 depicts the architecture of the robot controller, which is partly under development at the moment. Above the technical controller for the robot, a Cognitive Control Unit (CCU) [9] is used to control the assembly process. The CCU is based on the cognitive software architecture Soar [34], which aims at simulating the human cognition during decision making. In order to establish both a flexible and for the human operator comprehensive automation, a generic knowledge base in terms of if-then production rules has been developed [35,36]. A simple product specification including type, position, and rotation of the individual components suffices to derive autonomously the optimal assembly sequence at runtime. The order of the assembly tasks is chosen according to human assembly strategies that were identified in prior empirical studies [30,35]. Up to now, the assembly tasks are translated automatically into the necessary robot control (RC) programs only for an assembly cell using an industrial robot [37]. Nevertheless, work for controlling the above mentioned workplace using the LWA is in progress, in order to support direct human-robot cooperation.

Regarding more complex ergonomic work conditions, a Graph-based Assembly Sequence Planner (GASP) was developed [9]. It operates on an assembly graph that contains all valid assembly sequences of the product to be assembled. In order to avoid hazardous and ergonomic uncomfortable assembly actions, the GASP influences the decisions of the CCU by weighting the possible actions. Using the graph the GASP can benefit from much more knowledge than the CCU, which is limited to the next assembly step. In combination, both are able to improve the ergonomic work conditions significantly [32].
4. Summary and outlook

Today’s production lines of companies are usually either fully automated or require manual efforts by the human operator that are not negligible. Up to now, direct human-robot cooperation does not occur, not least because of the missing legal framework in terms of standards and norms. However, combining the power of both, human and robot, make the production more effective and efficient. One approach is to establish a joint workplace, where human and robot assemble one product in the same workspace together. While the robot assists, for instance, with handling components or performing tasks that require high precision, the human takes over tasks that cannot be done by the robot for sensorimotor reasons, such as the assembly of limp components. In order to design such a future workplace, this work summarizes the requirements that result from direct human-robot cooperation. They are presented with respect to the phases of the product life cycle, namely manufacturing, distribution, utilization, and reuse. Technical and human-related requirements are described as well as normative requirements, as far as the corresponding standards already exist. The designed workplace has been implemented as an early prototype based on the Robot Operating System (ROS) and a cognitively automated assembly planner.

Future steps will certainly address the finalization of the implementation of the above requirements including, for instance, the ergonomic alignment of the workplace as well as the linkage between the CCU and ROS. In addition, user studies are planned to give evidence of the planning results that were obtained so far by means of simulations.

Acknowledgements

The authors would like to thank the German Research Foundation DFG for the kind support within the Cluster of Excellence “Integrative Production Technology for High-Wage Countries”.

References

[1] J. Krüger et al., Cooperation of human and machines in assembly lines, CIRP Annals - Manufacturing Technology 58 (2009) 628-646
[2] M. Faber et al., Requirements for Modeling the Human Operator in Socio-Technical Production Systems, in: R. Schmitt and H. Bosse (Eds.), The 11th International Symposium on Measurement Technology and Intelligent Instruments, 2013
[3] H. Bley et al., Appropriate Human Involvement in Assembly and Disassembly, CIRP Annals - Manufacturing Technology 53 (2004) 487-509
[4] Y. Shen, G. Reinhart, Safe Assembly Motion - A Novel Approach for Applying Human-Robot Co-operation in Hybrid Assembly Systems, in: 2013 IEEE International Conference on Mechatronics and Automation (ICMA), 2013, pp. 7-12
[5] DIN EN ISO 10218-1:2011, Robots and robotic devices - Safety requirements for industrial robots - Part 1: Robots (ISO 10218-1:2011); German version EN ISO 10218-1:2011
[6] ISO/TS 15066, Robots and robotic devices – Collaborative robots
[7] H.-K. Lee et al. Dual-Mode Capacitive Proximity Sensor for Robot Application: Implementation of Tactile and Proximity Sensing Capability on a Single Polymer Platform Using Shared Electrodes, IEEE Sensors Journal 9 (2009) 1748-1755
[8] S. Phan et al., Capacitive skin sensors for robot impact monitoring, in: 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2011, p. 2992-2997
[9] M. Faber et al., Flexible and Adaptive Planning for Human-Robot Interaction in Self-Optimizing Assembly Cells, in: S. Trzcielinski and W. Karwowski (Eds.), Advances in The Ergonomics in Manufacturing: Managing the Enterprise of the Future, AHFE Conference, 2014, pp. 273-283
[10] H.-J. Franke, Methodische Schritte beim Klären konstruktiver Aufgabenstellungen, Konstruktion 27 (1975) 395-402
[11] DIN EN ISO 14738:2009, Safety of machinery - Anthropometric requirements for the design of workstations at machinery (ISO 14738:2002 + Cor. 1:2003 + Cor. 2:2005); German version EN ISO 14738:2008
[12] VDI 3657:1993, Ergonomical designing of packaging work stations
[13] ISO 13854:1996, Safety of machinery - Minimum gaps to avoid crushing of parts of the human body
[14] DIN EN ISO 13855:2010, Safety of machinery - Positioning of safeguards with respect to the approach speeds of parts of the human body (ISO 13855:2010); German version EN ISO 13855:2010
[15] DIN EN ISO 13857:2008, Safety of machinery - Safety distances to prevent hazard zones being reached by upper and lower limbs (ISO 13857:2008); German version EN ISO 13857:2008
[16] EN 953:2009, Safety of machinery - Guards - General requirements for the design and construction of fixed and movable guards; German version EN 953:1997+A1:2009
[17] DIN EN ISO 14119:2014, Safety of machinery - Interlocking devices associated with guards - Principles for design and selection (ISO 14119:2013); German version EN ISO 14119:2013
[18] DIN EN ISO 1005-4:2009, Safety of machinery - Human physical performance - Part 4: Evaluation of working postures and movements in relation to machinery; German version EN 1005-4:2005+A1:2008
[19] DIN EN ISO 12100:2010, Safety of machinery - General principles for design - Risk assessment and risk reduction (ISO 12100:2010); German version EN ISO 12100:2010
[20] DIN EN ISO 9241-110:2006, Ergonomics of human-system interaction - Part 110: Dialogue principles (ISO 9241-110:2006); German version EN ISO 9241-110:2006
[21] DIN EN ISO 13850:2008, Safety of machinery - Emergency stop - Principles for design (ISO 13850:2006); German version EN ISO 13850:2008
[22] DIN EN ISO 10218-2:2012, Robots and robotic devices - Safety requirements for industrial robots - Part 2: Robot systems and integration (ISO 10218-2:2011); German version EN ISO 10218-2:2011
[23] DIN EN ISO 13849-1:2008, Safety of machinery - Safety-related parts of control systems - Part 1: General principles for design (ISO 13849-1:2006); German version EN ISO 13849-1:2008
[24] T. Missala, Paradigms and Safety Requirements for a New Generation of Workplace Equipment, International Journal of Occupational Safety and Ergonomics (JOSE) 20 (2014) 249-256
[25] DIN EN 1037:2008, Safety of machinery - Prevention of unexpected start-up; German version EN 1037:1995+A1:2008
[26] P.A. Lasota et al., Toward Safe Close-Proximity Human-Robot Interaction with Standard Industrial Robots, in: 2014 IEEE International Conference on Automation Science and Engineering (CASE), Taipei, Taiwan, 2014, pp. 339-344
[27] prEN/TS 62046:2009, Safety of machinery - Application of protective equipment to detect the presence of persons (IEC/TS 62046:2008); German version CLC/TS 62046:2008
[28] DIN EN ISO 13856-1:2013, Safety of machinery - Pressure-sensitive protective devices - Part 1: General principles for the design and testing of pressure-sensitive mats and pressure-sensitive floors (ISO 13856-1:2013); German version EN ISO 13856-1:2013
[29] DIN EN ISO 61496-1:2014, Safety of machinery - Electro-sensitive protective equipment - Part 1: General requirements and tests (IEC 61496-1:2012); German version EN 61496-1:2013
[30] M. Mayer, C.M. Schlick, Improving operator’s conformity with expectations in a cognitively automated assembly cell using human heuristics, in: S. Trzcielinski; W. Karwowski (Eds.) Advances in Ergonomics in Manufacturing, CRC Press, Boca Raton, FL, USA, 2012
[31] S. Kuz et al., Anthropomorphic Design of Human-Robot Interaction in Assembly Cells, in: S. Trzcielinski, W. Karwowski (Eds.) Advances in The Ergonomics in Manufacturing: Managing the Enterprise of the Future, AHFE Conference, 2014, pp. 265-272
[32] M. Faber et al., Adaptive assembly sequence planning with respect to ergonomic work conditions, in: Proceedings of the 19th Triennial Congress of the IEA, 2015 (accepted)
[33] M. Quigley et al., ROS: an open-source Robot Operating System. In: IEEE International Conference on Robotics and Automation (ICRA), Workshop on Open Source Software, 2009
[34] J.E. Laird, The Soar Cognitive Architecture,MIT Press, 2012
[35] M. Mayer et al., Cognitive Engineering of Automated Assembly Processes, Human Factors and Ergonomics in Manufacturing & Service Industries 24 (2014) 348-368
[36] M. Faber et al., Design and Implementation of a Cognitive Simulation Model for Robot Assembly Cells, in: D. Harris (Ed), Engineering Psychology and Cognitive Ergonomics. Understanding Human Cognition, Springer Berlin Heidelberg, 2013, pp. 205-214
[37] C. Brecher et al., Design and Implementation of a comprehensible Cognitive Assembly System, in: S. Trzcielinski, W. Karwowski (Eds.) Advances in Ergonomics in Manufacturing, CRC Press, 2012, pp. 272-281