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Integrating Manufacturing Education with Industrial Practice using Teaching Factory Paradigm: A Construction Equipment Application

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Abstract

The importance of leveraging manufacturing teaching and training up to the standards of the current and future needs is obvious. Recent studies have pointed out the urgent need for future engineers and knowledge workers to adopt teaching curricula in order to be prepared to cope with the increasing industrial requirements of the factories of the future. The current study presents the evolution of the Teaching Factory concept and its application to a real-life pilot. The Teaching Factory paradigm comprises the industrial project, the relevant educational approach and the necessary ICT configuration for the facilitation of interaction between industry and academia. The current status of the paradigm is tested on a real-life pilot, between a university and a construction equipment factory. The conclusions of the pilot, show the promising nature of the Teaching Factory and the numerous benefits accruing, both for academia and industry.

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1. Introduction

Manufacturing enters a new era, where blue-collar workers and engineers will need novel life-long learning schemes to keep up with the rapid advances in production related technologies, tools and techniques. In Europe alone, manufacturing accounts for more than 28% of the GDP, even in today's economic recession [8]. Considering the importance of manufacturing as a wealth generating activity for any nation, the promotion of excellence will become a strategic target in the years to come. Manufacturing education, as identified by Manufuture [9], will comprise a major driver towards that direction. However, teaching and training have not kept pace with the advances in technology. The current practice is deficient in providing the workers with a continuous delivery of engineering competencies and strong multi-disciplinary background. In addition, the lack in soft skills in comparison with IT skills has been widely acknowledged by employers [11]. The innovation performance needs boosting. Although innovative ideas and research outcomes are abundant, their transformation into new products and processes is mistreated. Modern concepts of training, industrial learning and knowledge transfer schemes can contribute to improving the innovation performance of European manufacturing [2]. Nonetheless, manufacturing is a subject that cannot be treated effectively only inside a classroom, whilst industry can only evolve through the adoption of new research results. On the one hand, the research results typically remain within the education institutions and their adoption by industry rarely happens, whilst on the other hand, industry often hesitates to adapt to the new technological advances.

Society is always appreciative of skills. Several studies have revealed the relationship between educational quality and economic growth, highlighting the fact that the human capital is a key to growth. Indicatively, each year of schooling has been reported to boost long-run growth by 0.58 percentage points [6], while performance on international student achievement tests has been reported to have a powerful impact on growth. On the other hand, skills' shortages are reported to have had a negative effect on innovation performance [11]. In 2009, the European Union

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had 38.1 million of highly qualified knowledge workers by virtue of both education and occupation [5]. On top of that, results of forecast studies show a considerable shift in labour demand, towards skilled workers, by implying that future jobs will become even more knowledge- and skill-intensive [1]. A recent survey in Mechanical Engineering associations, reconfirmed the forecasts about future skills' shortages and gaps in Europe [7]. Most associations were concerned about the bottlenecks in filling certain occupations / job functions in companies. To effectively address these emerging challenges for manufacturing education and skills delivery, the educational paradigm in manufacturing needs to be revised.

In the last decade, the Teaching Factory concept has gained major interest, especially in the US, resulting in a number of educational and / or business pilot activities. Many educational institutions have tried to bring their educational practice closer to industry [2]. Industrial projects that take place in the Teaching Factory provide students with the integration of learning experiences into a contextual setting, where emphasis is given to competency and effective application. Popular topics for Learning Factories include energy efficiency optimisation and lean management of production processes and methods [4, 12]. Most of the reported applications of the Teaching Factory paradigm simulate the key features of an industrial environment in an academic setting, using model production equipment [13]. A drawback of these approaches is the fact that the dedicated production equipment, which is installed on the academic settings, can soon become obsolete. The pace in which production systems evolve has significantly increased over the last decades in order for shorter product lifecycles, imposed by the world markets to be met [14]. Therefore, many new technologies and approaches have been introduced to the industrial practice that hinders the succession of an academic setting.. Although not all businesses may use state-of-the-art technologies, the flexibility of dedicated academic settings is very low for the anticipation of a diversified set of manufacturing problems. Consequently, dedicated learning factories have the intrinsic limitation of narrowing down their scope based on the existing equipment. The Teaching Factory approach presented in this study aims at a much broader use of novel learning methods for the introduction of young engineers to a wide spectrum of manufacturing problems.

It becomes obvious that new approaches are required for manufacturing education in order to i) modernise the teaching process and bring it closer to the industrial practice ii) leverage industrial practice through new knowledge, iii) support the transition from the manual to the future knowledge workers and shorten the gap between resource-based manufacturing (labour and capital) and knowledge-based manufacturing (information and knowledge) and iv) establish and maintain a steady industrial growth. At conceptual level, an extended Teaching Factory paradigm, based on the knowledge triangle notion, has been suggested [10]. The aim is to effectively integrate education, research and innovation activities into a single initiative involving industry and academia. Towards that end, the proposed Teaching Factory paradigm focuses on integrating industry and academia, through novel adaptations to the teaching / training curricula, achieved by the deployment of ICT-based delivery mechanisms.

2. The Teaching Factory concept

The Teaching Factory concept is based on the knowledge triangle notion aiming to become a new paradigm of both academic and industrial learning [3, 10]. The mission is to provide engineering activities and hands-on practice under industrial conditions for university students, while taking up research results and industrial learning activities for engineers and blue-collar workers. Research, education and innovation are three fundamental and strongly interdependent drivers of the knowledge-based society. Therefore, the Teaching Factory aims to seamlessly integrate all three cornerstones into a single initiative in order to promote the future knowledge-based, competitive and sustainable manufacturing. The Teaching Factory has emerged as a promising concept of integrating the factory environment with that of the classroom. The concept of the Teaching Factory has its origins in the medical sciences discipline and specifically, in the paradigm of the teaching hospitals, namely the medical schools operating in parallel with hospitals. It aims to integrate the learning and working environments, from which realistic and relevant learning experiences arise.

The "factory-to-classroom" concept of the Teaching Factory aims at transferring the real production/manufacturing environment to the classroom. The real life production site needs to be used for teaching purposes in order to enhance the teaching activity with that of the knowledge, existing in the processes of every day industrial practice. Towards this direction, delivery mechanisms that will allow the students in a classroom to apprehend the production environment, in full context, need to be defined and developed. This concept mainly focuses on the "virtual enterprise" type of operations with training services delivered on a virtual basis. The configuration layout of the factory-to-classroom concept should follow a modular approach to allow flexibility on its application and operation. Multiple layout options are possible when different modules of the Teaching Factory are being combined. Moreover, such sessions could accommodate multiple knowledge receivers. As depicted in Fig. 1, the configurations of the Teaching Factory sessions could follow either a "one-to-one" approach that is one factory to one classroom, or, a "one-to-many" approach, which involves one factory, interacting with many classrooms at the same time.

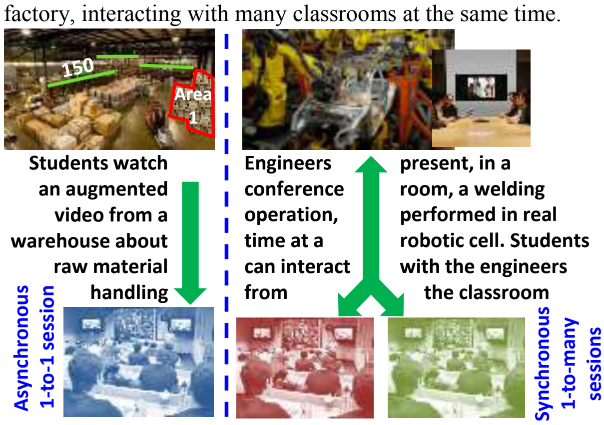

Fig. 1: Different Teaching Factory Layouts

The modularity of the Teaching Factory concept is presented in four categories, whose modules describe the options of the factory-to-classroom operation. The different modules listed in the four categories can be combined with various configuration layouts. The modules mentioned must be recognised as exemplary. The first category is the "Factory", which represents the different modules that correspond to the production areas and processes, involved in the Teaching Factory. The second category defines the curriculum / study content delivered in the Teaching Factory. The third category is populated by the delivery mechanism modules. The delivery mechanisms are responsible for the communication of knowledge and interaction capabilities between the factory and the classroom. The expression "Delivery Mechanism" does not imply a linear delivery of the knowledge. Knowledge, and particularly competencies are constructed by the participants with the help of the IT-infrastructure and the teaching staff. Category four, pictures the delivery ICT technology, for example that dedicated to video conferencing or web services. Finally, the fifth category includes the courses, corresponding to the configurations that will accommodate the Teaching Factory session, within the educational activities. In Fig. 2, three exemplary indicative options are illustrated in order for the modularity concept to be proven. The advantage of this modular approach stems from the fact that, depending on the factory and curriculum, which the Virtual Teaching Factory will operate in, different options allow flexibility on any possible limitations. These limitations will result from the technological infrastructure available, time and cost limitations. The IT-Infrastructure Layout specifies the delivery mechanisms and defines the interfaces of the IT-Infrastructure with the classroom, the conference room, the factory and further connectable devices. Additionally, it describes the way that the knowledge transfer from the factory to the students will be managed.

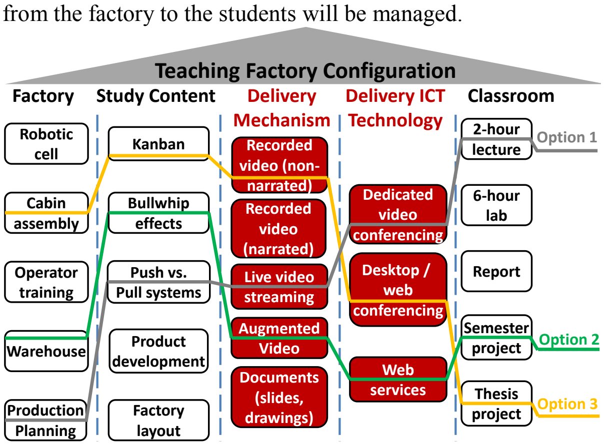

Fig. 2: Multiple layout options for factory-to-classroom operations

3. Industrial project setup

The "factory-to-classroom" operating scheme of the Teaching Factory, aims at transferring knowledge from the factory to the classroom. The implementation of this operation is carried out through the adoption of an industrial project in the context of academic practice. The purpose of the Teaching Factory project is to bring together, in overlapping time and context, the industrial and academic practices (see Fig. 3).

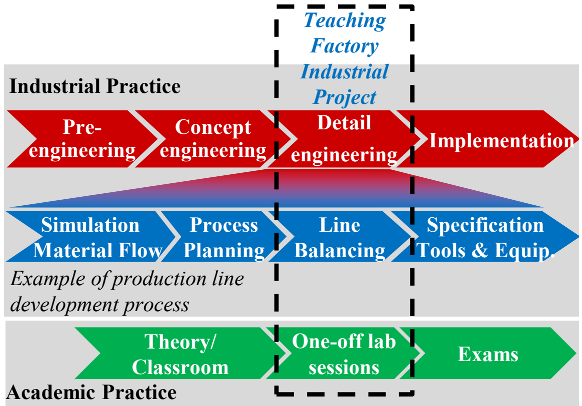

Fig. 3: Integrating industrial and academic practices

The industrial problem can have certain duration that is relevant to the problem to be handled in the industrial side. This problem will be deriving from a specific set of tasks, included in the product / production lifecycle. For example, an industrial project can focus on the line balancing of a new production line, which is normally carried out, in industrial practice, during the detailed engineering phase (see Fig. 3). It is broken-down into sub-tasks distributed to student teams. The students work on a solution of this problem using modern ICT technologies for communicating with the engineers and tools necessary for the development and validation of their ideas and solutions. The project is supported by an educational approach that integrates the details and logistics into the academic practice, together with an ICT approach that facilitates the interaction between factory and classroom.

4. Educational approach

The integration of the Teaching Factory industrial project is made through a weekly cycle of sessions, comprising supporting classes, project work and live interactions with the factory. An indicative weekly cycle is depicted in Fig. 4.

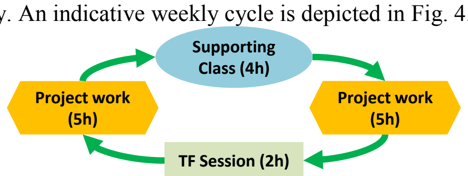

Fig. 4: Indicative weekly cycle of the Teaching Factory Educational approach

Each "Teaching Factory" session is characterised by a certain live interaction with the factory. This interaction includes discussions, sharing of presentations, live videos from the production and other knowledge delivery mechanisms, depending on the content of the problem. In between the live sessions, the students have to carry out project work, which may involve the experimentation of their solutions on industrial software tools or the analysis of data and models to derive conclusions and new solutions. The project work is carried out before and after the supporting classes, comprising the third component of the weekly cycle. During supporting classes, the student teams brainstorm their next steps in order to come up with a solution. The supporting classes are moderated by an academic supervisor, who is also responsible for triggering the discussions and providing guidelines in search of solution paths. Each member collaborates with the rest of its team members or even with the other teams. This educational approach has a two-fold objective: i) it aims to integrate the need for live interaction with the factory, via tools and practices available in the academic environment and ii) it allows and encourages certain soft skills to be developed and exercised among the students. The teams compete with each other in order to present the finest solution or to deliver the best presentation. The communication skills of the students are tested considering that they have to interact, sometimes in a foreign language, with people from industry. Leadership skills are necessary for overcoming problems or for a team to be organised.

5. ICT configuration

The real-life operation from the factory needs to be virtually presented to the university group of engineering students, who undertake the industrial project. Audio-visual components, such as cameras and microphones hooked up on a networking infrastructure can be used, while the students remain in their class-room. On the factory site, engineers make presentations of the specific manufacturing system in connection to the industrial project, whilst being watched by the students and contextually supplemented by a teaching staff member of the university. The engineer first describes the process and introduces the corresponding production organisation. Subsequently, the realistic problem associated with this process is presented and visually shown.

The students are able to interact with the engineers in real-time, ask questions and discuss initial ideas for solutions. The teaching staff member records the session, enhances it with appropriate annotations and holds a couple of coaching sessions with the students to elaborate their understanding even further and give directions. Additionally, the engineers give frequent distance learning seminars, to support students during the project. The students collaborate in groups in order to identify possible solutions to any problem arisen, making use of experimenting techniques such as simulation.

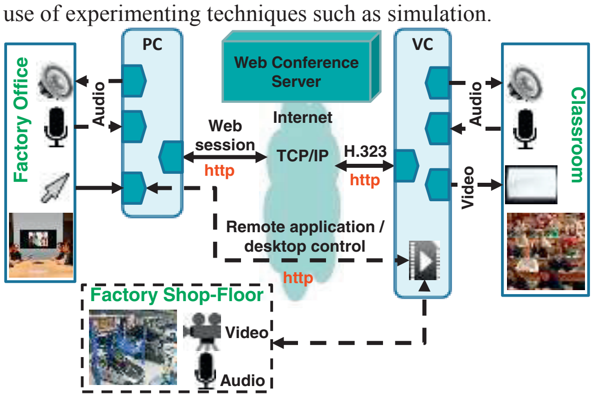

Fig. 5: Example of ICT layout

The communication and interaction during the Teaching Factory sessions, between the factory and the classroom, are facilitated by web-based meeting tools for the sharing of presentations and videos. Fig. 5, shows an example of the ICT technologies layout that can be used for the communication and interaction among the different actors. In the factory, the engineers communicate through a PC via audio, using microphones and speakers, while sharing through web session presentations the description of the problem. If a live connection with the factory shop-floor is infeasible, a recorded video can be downloaded on the video-conference system in the classroom and be remotely controlled by the engineer at the factory office. In classroom, the students and the teaching staff members communicate with the engineers via microphones, speakers and large TV screens.

6. Pilot run outcomes

The concepts and approaches presented in this study have been tested on a real-life pilot between students, in the Department of Mechanical Engineering and Aeronautics, of the University of Patras and engineers working at a construction equipment factory in Europe. The industrial problem addressed was the line balancing of a new production area for the construction equipment factory. The factory produces wheel loaders among other construction equipment products. The pilot was carried out over a period of seven weeks. Each week, the Teaching Factory session would take place in the form of seminars between the students in the classroom and the engineers in the factory. The subjects allocated in each week cover from introduction to the problem, discussion and initial theoretical approach, to evaluation of draft model, results and presentation of solutions. The student teams were divided into four (4) groups of five (5) persons. The project was carried out by the students in the context of “Introduction to the Manufacturing Technology” which was a mandatory 2nd year course. For logistical reasons, it was decided that only 20 students would participate in this pilot. The students were supervised by four research engineers. In the factory, at least four to five people were engaged in the pilot, by providing the details and the problem’s background and for supporting the students. The classroom dedicated to each Teaching Factory session of the students, was specifically built for “tele-learning” operations and provided the necessary means of hosting this pilot, while maintaining a good interaction quality (Fig. 6).

Fig. 6: The Teaching Factory sessions were carried out in a dedicated “tele-learning” classroom

The pilot was focused on a material flow simulation project. The background of this project was a new manufacturing concept of wheel loaders, planned for future production. Today, large fixtures for complete manufacturing (welding and machining) are used. The future target is that smaller fixtures are used, requiring smaller and cheaper machines, requiring also new material feeding that is not fully defined. A material mall is planned, but without detailed plans, regarding the feeding concepts of the material entering the plant and its final position at the assembly line. The current ideas and proposals have to be verified.

The industrial project was targeted at under-graduate students, who performed the validation of new concepts for the factory, by using discrete event simulation software. Among the actors involved in the industry, were production engineers and simulation experts. The industrial problem was broken down into two (2) separate tasks, each one assigned to two student teams.

The first task focused on the welding area of the wheel-loader's rear-frame. In this area, the four sides of the frame (sides, waist and engine) are welded together. The students were asked to run experiments in order to define the workload strategy of each station, to investigate into the effects of the workload on the system's output, given a mean downtime and how sensitive the system can be in any deviations of the processing times. The input of the students for the execution of these experiments had to do with the interval up-time of the equipment, the interval processing time and transport times in the area, and the working shifts data.

The second task of the industrial problem was related to the planning of the material kitting area and the train routes, in terms of human resources and materials. The students were required to provide an understanding of the optimal positions of the different component types, depending on variant penetration and frame sequence, while defining the location of the material containers and the human resources required for carrying out the material feeding process to the welding area. In order for that to be accomplished, the students had to develop their own model of the material kitting area and train routing. The input given to them included the layout of the transportation routes, the Bill of Materials (BoM) for each variant, the characteristics of each component (size, weight, etc.), the production sequence and the shift data. The students had to use a discrete event simulation software in order to model and simulate the operation of this production area as well as its train material delivery system (besides the planning of the material storage area). They experimented with the model and used statistical analysis methods to evaluate the results, suggest their own solutions and recommend them to the factory. The engineering subjects introduced to the students (theory and practice) during the course of the Teaching Factory pilot, included line balancing, production attributes (Availability, MTBF, MTTR, Cycle time, WIP, Throughput, etc.), discrete event simulation modelling and experimentation and statistical analysis of data.

One team experimented with the availability of the robotic cells based on varying processing times. The input parameters used were the varying availability (related to a robotic wear equation) based on theoretical values. The objective was to find out the specific processing time for maximising the availability. The findings were that the theoretical optimal output of the system occurred for a 27-minute cycle time. Consequently, the waiting time and the blocked state percentage were decreasing as the MTBF was increasing.

The second team approached the issue of workload balancing by considering the availability as constant. Having a specific target output for the system, the team worked on a discrete-event simulation model in order to carry out a set of experiments for the extraction of data to be used in a statistical analysis. Using design of experiments, ANalysis Of Means (ANOM) and ANalysis Of Variance (ANOVA), the students were able to identify certain factors that affected the system's performance, while determining the optimal processing time for achieving the output target. The students achieved to identify serious bottlenecks that were creating disturbances in the assembly line of the production area. The pallet systems and cooling stations had a major effect on the system's cycle time. The suggestions of the team could lead to an updated production for the avoidance of bottlenecks.

For the second task of the industrial case, the student teams addressed the problem of material kitting area planning. First, they built their own discrete-event simulation model to experiment with their designs and investigate the best solution regarding the resources required for the train route. Following on to the development of the model, the teams planned the distribution of the material components in the kitting area. This allowed for the calculation of the times for every scenario tested for the train route. The teams' experiments were based on two different scenarios. One team considered a scenario whose train would perform the material delivery and its operator would be responsible for the loading of components on the train kits. The other scenario considered two human operators and one train whose second operator would assist with the loading of the components in the kitting area. The experiments showed that in the first scenario, the cycle time would be 30 mins which is above the target of 27 mins. The second scenario, resulted in a 25'33'' cycle time and thus, it was the one suggested by the team. The outcome of the students' study was that the initial consideration of the factory would result in greater investment and running costs.

7. Conclusion and Future work

The Teaching Factory is a concept for changing the educational paradigm in manufacturing into a novel scheme that supports the needs of "knowledge workers" in the factories of the future. The current work presents a novel approach for integrating industry with academia under the Teaching Factory concept, tested on real pilot applications.

The outlook of the pilots is very hopeful and beyond the initial expectations of both industry and academia. The main purpose was that the capabilities and added value of the Teaching Factory be demonstrated in various operational schemes. The execution of the pilot demonstrated the great opportunity for revitalising manufacturing education through the adoption of similar teaching schemes to the ones followed in this study. The modular nature of the Teaching Factory may suit the needs and limitations of both the academia and industry. Not all manufacturing problems can have their solution worked out via methods selected for the pilot cases of this study. This is the reason why the Teaching Factory asks for a high-degree of modularity when adopted for academic and industrial practice. Depending on the manufacturing problem or application, different delivery mechanisms are required in order to effectively cover the Teaching Factory operation. There is room for the ICT technologies of the Teaching Factory to be improved in terms of didactic content. The content used needs to be prepared and presented in a well-defined didactic manner. Furthermore, another critical point that needs careful consideration in involving real industrial problems is when sensitive data are shared from industry to academia. This can be an impediment to the completeness of information required to carry out the Teaching Factory. However, there are ways of surpassing such problems, namely the signing of non-disclosure agreements, as well as the pilots carried out in the context of the present study. More serious obstacles turn up when human operators (e.g. in factory shop-floor) are to be involved in the Teaching Factory's operation. For example, issues concerning the protection of sensitive personal data could be raised, in case of having a live image transmitted from the work that is carried out by a human operator.

From the academic point view, the Teaching Factory scheme was a new experience for both the students and the faculty members. It provided a new kind of teaching that was not available in theoretical lectures, or in one-time labs. The Teaching Factory scheme, enabled the students to deepen certain knowledge topics and apply that in practice, while addressing real-life problems, and working in view of actual deadlines and industrial practice terms. At the end, their work would have a real impact outside the academic environment. In general, following the assessment of the pilot and the feedback gathered, the students believed that they found a practical solution to the problem and their results showed some points in the model that could be improved and lead to a better output. The pilot experience was relevant to a real case scenario that helped with the comprehension of manufacturing systems in general. The students came in contact with a company's real problem about process planning and the simulation of a processing line. It was perceived as a very constructive project for gaining knowledge in manufacturing by approaching a real industrial problem and working on real data. A critical aspect attributed to the success of this pilot was the fact that the engineers were able to spend enough time on sufficiently presenting and explaining the problem to the students. However, the amount of time that is usually required for such work to be carried out by engineers can be considered insignificant. Indicatively, their time spent is accounted for about twenty per cent (20%) of the total time in order for the given problem to be addressed by the students.

Regarding the industrial point of view, the Teaching Factory provided ideas and solutions that would not have been considered during the standard company processes of solving such problems. During the pilot a wide range of solution proposals came up, which consequently resulted in better decision support. The factory people had the chance to interact with a pool of students with a new way of thinking and problem solving capacity. In some cases, there were students, who approached the problem with real talent and out-of-the-box thinking. The feedback gathered by the engineers involved in the pilot, showed that the final solution was extensive and many aspects were investigated, while being useful for future preparation work. It is hard to evaluate the optimality of the solution until production is running; however, preliminary estimations indicated promising results. In general, it was considered a good experience from both ends involved. An important conclusion having derived from the pilot was the fact that the long distance between the factory and the university did not have a negative impact on the results. The results were both a confirmation of the company's own planning and an additional contribution with new proposals and solutions.

Future work on the development of the Teaching Factory paradigm includes the definition of a new business model facilitating the bi-directional knowledge flow through a Teaching Factory Network, by establishing learning and training channels, for the communication of manufacturing knowledge among multiple remotely located "factories" and "classrooms". The availability of content and resources is the main limitation identified during the pilots presented in this paper. The definition of a Teaching Factory Network will allow for an efficient allocation of the content and the use of the resources.

Acknowledgement

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References

[1] CEDEFOP. Skills and Supply Demand in Europe, Medium-term forecast up to 2020; 2010.

[2] Chryssolouris G, Mavrikios D, Mourtzis D. Manufacturing Systems: Skills & Competencies for the Future", Procedia CIRP, Keynote paper of the 46th CIRP Conference on Manufacturing Systems 2013;7:17-24.

[3] Chryssolouris G, Mavrikios D, Papakostas N, Mourtzis D. Education in Manufacturing Technology & Science: A view on Future Challenges & Goals. Inaugural Keynote, Proceedings of the International Conference on Manufacturing Science and Technology, Melaka, Malaysia, August 2006.

[4] Dinkelmann M, Riffelmacher P, Westkämper E. Training concept and structure of the Learning Factory advanced Industrial Engineering, In: Enabling Manufacturing Competitiveness and Economic Sustainability: Proceedings of the 4th International Conference on Changeable, Agile, Reconfigurable and Virtual Production (CARV 2011), ElMaraghy, H. (ed.), Montreal, pp. 624- 629. 2011.

[5] Eurostat. Science, technology and innovation in Europe. Eurostat Pocketbook 2011.

[6] Hanushek AE, Wößmann L. The Role of Education Quality in Economic Growth. Policy Research WP 4122, World Bank. Washington, D.C. 2007.

[7] Ifo Institute, Cambridge Econometrics, Danish Technological Institute. Study on the Competitiveness of the EU Mechanical Engineering Industry, Final Report 2012.

[8] IMF (International Monetary Fund), World Economic Outlook – Hopes, Realities, Risks, World Economic and Financial Survey, April 2013, URL: http://www.imf.org/external/pubs/ft/weo/2013/01/pdf/text.pdf

[9] Manufuture High Level Group and Implementation Support Group. ManuFuture Platform - Strategic Research Agenda, assuring the future of manufacturing in Europe 2006.

[10] Mavrikios D, Papakostas N, Mourtzis D, Chryssolouris G. On industrial learning & training for the Factories of the Future: A conceptual, cognitive & technology framework, Journal of Intelligent Manufacturing, Special Issue on Engineering Education 2011;24/3:473-485.

[11] Tether B, Mina A, Consoli D, Gagliardi D. A Literature Review on Skills and Innovation. How Does Successful Innovation Impact on the Demand for Skills and How Do Skills Drive Innovation? A CRIC Report for The Department of Trade and Industry 2005.

[12] Tisch M, Hertle C, Cachay J, Abele E, Metternich J, Tenberg R. A systematic approach on developing action-oriented, competency-based Learning Factories, Procedia CIRP 2013;7:580-585.

[13] Wagner U, AlGeddawy T, ElMaraghy H, Müller E. The State-of-the-Art and Prospects of Learning Factories, Procedia CIRP 2012, 3:109-114

[14] Chryssolouris G, Efthymiou K, Papakostas N, Mourtzis D, Pagoropoulos A. Flexibility and complexity: is it a trade-off?, International Journal of Production Research 2013;51/23-24:6788-6802