Volume 16, Number 2, 2014

Global Journal of Engineering Education

Characterisation of the student perception of the concept of flexibility in the manufacturing domain: highlighting the patterns of effective learning

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ABSTRACT: This work introduces a phenomenographic analysis of the concept of flexibility in the domain of production science. Flexibility is a cornerstone in the education of industrial and production engineers; however, it still appears as a broadly and even inconsistently defined construct. In order to clarify what is or should be learnt, this work analyses first the established literature to extract a *working* characterisation of the flexibility concept. The resulting understanding is then used to represent the experts' perception of the topic, which in turn is used as the ideal level of understanding that a student should achieve herself/himself when studying such a concept. The second phase of the work aims at disclosing and classifying the multifaceted perceptions of flexibility that two classes of industrial engineering students have after two courses in which the focal concept of manufacturing flexibility has been presented using two different approaches. The research is based on a survey completed by students. The data collected have consequently been structured into a finite set of clusters according to: a) the level of understanding of the key concept; and b) the nature of the shown knowledge. The classification is, then, the basis for defining an epistemologically sound approach to develop suitable teaching and learning activities to ensure optimal acquisition of the concept of flexibility.

Keywords: Flexibility, industrial automation, phenomenography

INTRODUCTION

Modern higher education organisations are facing an increasingly dynamic environment: students with different backgrounds and specific requirements, changing pedagogical means and global competition are among the emerging trends that are shaping future universities. This is even more dramatic in the technology domain where a more and more rapid process of innovation continuously kills the use of more traditional competencies and equipment. Consequently, in order to keep offering effective and high quality education, the main focus of well-designed engineering programmes and courses must shift from knowing a particular embodiment of a given technology towards having more soft skills, like being able to search for the information by oneself and to look at it critically, along with being able to decide, plan and execute one's own formation endeavours or sound delegation of responsibilities.

Traditional approaches, still in use in many university courses, offer lectures and lone textbook study. This *transmissive pedagogy* is based on the assumption that student are like boxes that can be filled with notions simply by exposing them to knowledge. This is as far from the truth as it is possible to be! Students have different backgrounds, motivations and inclinations towards the learning process. A better characterisation of such aspects is necessary to design effective learning moments that must act in different moment of the learning process [1][2].

As an answer to the above requirements a more holistic approach based on facilitating good learning by letting the students experience the studied object in different contexts or with different embodiments has been proposed. *Variation* is, thus, the key to effective learning [3]. In other words, the learners can build up reliable knowledge by disclosing the pattern of variation of the studied phenomena. Knowing the spectrum of student perception of a given phenomenon is, thus, the starting point for good course design.

The work presented in this article is a phenomenographic study of the perception that production engineering students, at the end of two different courses, have of the concept of flexibility in manufacturing science. The word *flexibility* is often abused and not univocally understood within the manufacturing science domain and, in particular, in the context of industrial automation. Since the advent of industrial robots in the 1960s, researchers and practitioners have been attributing different meanings to this common word. This has generated a highly articulated concept, spanning from the capability of a system to increase the production volumes, to having the ability to handle product mix variation. Several authors have tried to count the current meanings of such a word in manufacturing and one found more than 50! [4].

In spite of this fuzziness in both the definition and scope, the concept of flexibility remains as one of the cornerstones in the curriculum of industrial and production engineers, and it appears in many courses in the Bachelor's and Master's degree studies. The apparent paradox that higher education institutions have to teach things that are not even well-defined and agreed in the scientific world is, in fact, quite a usual practice. The paragraphs that follow provide an overview of the subject that can serve the reader as a blueprint to go through the work and, eventually, achieve an understanding of the findings.

BACKGROUND

Pedagogical Supporting Constructs

The analysis presented in this article has been carried out using a phenomenological approach. Such a methodology focuses on the study of the variation in ways people experience the construct and phenomena in a discipline. The assessment of such perceptions is not done in closed laboratories and on controlled variables, but is rather based on how the researchers engage with the people being analysed. Phenomenographers focus on how a certain set of people experience a given phenomenon, defined as second-order perspective (studying the world as seen), rather than the phenomenon itself, which instead is a first-order perspective (studying the world as such) [5][6]. Consequently, the result is not a quantitative measure of people knowledge, but a taxonomy that can capture salient aspects of the variation with which a particular phenomenon is understood. These salient aspects, in turn, can be exploited to expose possibilities to improve the learning experience.

One of the important variables in determining the way students perceive the studied object is the *cognitive level of complexity of their thinking in relation with the topic*. The simple ability to remember a formula and mechanically put numbers in it, does not insure that the student has grasped the underlying meaning of such relationships and that he/she will be able to apply it in unknown situations. The static cognitive domain can be classified for example with the famous Bloom's taxonomy [7], which depicts the development of intellectual skills related to a topic through the following six stages:

1. *Knowledge*: recall data or information.
2. *Comprehension*: understand the meaning, translation, interpolation, and interpretation of instructions and problems. State a problem in one's own words.
3. *Application*: use a concept in a new situation or unprompted use of an abstraction. Apply what was learned in the classroom into novel situations in the work place.
4. *Analysis*: separate material or concepts into component parts so that its organisational structure may be understood. Distinguish between facts and inferences.
5. *Synthesis*: build a structure or pattern from diverse elements. Put parts together to form a whole, with emphasis on creating a new meaning or structure.
6. *Evaluation*: make judgments about the value of ideas or materials.

The pattern towards high level understanding is another important dimension of phenomenographic analysis. As disclosed in the SOLO taxonomy, such patterns usually involve the following phases:

Quantitative phase:

1. Pre-structural: students only understand the subject at the individual word level, usually miss the point and use too simple a way of thinking about it.
2. Uni-structural: students' understanding focuses on only one relevant aspect of the subject.
3. Multi-structural: students' understanding focuses on several relevant aspects, but is treated as independent objects and concepts.

Qualitative phase:

4. Relational: different aspects of students' understandings have been integrated into a coherent body of knowledge.
5. Extended abstract: the integrated body of knowledge can be transformed into the higher level of abstract and be generalised to a new topic in the subject.

These constructs have been recapped here as they have been useful synthesis tools for analysing and troubleshooting the results of the focal analysis and, thus, helping to structure the research findings presented in this article.

FLEXIBILITY IN MANUFACTURING: AN EXPERT UNDERSTANDING

As seen above, phenomenography aims to disclose variations in students' perception of a given phenomenon. From this perspective, a successful learning process should bring the student from a little (if not none) initial understanding of the topic taught, to a level of awareness similar to one of an expert in the field [5]. In order to understand the result of this work it is, therefore, necessary to introduce the concept of manufacturing flexibility as it is understood and taught nowadays.

As was also pointed out in the introduction, *flexibility* is a buzzword prototype that has found its way into many definitions belonging to several technical disciplines. The average student of production or industrial engineering will also meet this word in many other domains: design theory, factory planning, manufacturing, decision making The common denominator among all these perspectives is that flexibility is an attribute that makes a system able to cope with *uncertainty* and *change*. This also means the *ease of modification* and absence of *irreversible rigid commitments*. Being a concept linked to potential change, unlike system performance, it is difficult to observe and measure [8]. As noted by many scholars, flexibility is not usually well defined and understood in the scientific world, yet it is a critical aspect of the competitiveness of a company and, thus, it must be a cornerstone in the education of every engineer [9][10].

In manufacturing science, the concept of flexibility is in general understood as the capability to reconfigure manufacturing resources in order to continue producing efficiently different products in response to, or to prompt, changes in the system's environment [4]. The introduction of industrial robots to handle welding in the automotive industry has put the emphasis on the concept such that it is still the object of intensive research efforts. Flexibility allows an organisation to achieve *economies of scope* in their manufacturing processes [11].

Flexibility can be applied to many aspects of the manufacturing domain. The following list presents a series of definitions (not univocally accepted!) as reported by [4]:

- *Machine flexibility* refers to the various types of operations that a machine can perform without requiring a prohibitive effort in switching from one operation to another.
- *Material handling flexibility* is its ability to move different part types efficiently for proper positioning and processing through the manufacturing facility it serves.
- *Operation flexibility* of a part refers to its ability to be produced in different ways.
- *Process flexibility* of a manufacturing system relates to the set of part types that the system can produce without major setups.
- *Product flexibility* is the ease with which new parts can be added or substituted for existing parts.
- *Routing flexibility* of a manufacturing system is its ability to produce a part by alternate routes through the system.
- *Volume flexibility* of a manufacturing system is its ability to be operated profitably at different overall output levels.
- *Expansion flexibility* of a manufacturing system is the ease with which its capacity and capability can be increased when needed.
- *Program flexibility* is the ability of the system to run virtually untended for a long enough period.
- *Production flexibility* is the universe of part types that the manufacturing system can produce without adding major capital equipment.
- *Market flexibility* is the ease with which the manufacturing system can adapt to a changing market environment.

This list gives the idea of the breadth of the topic. All the aspects and their possible correlations and mutual influences along with their impact on the company performance and strategies should be understood by production engineers. In view of this, it is clear that the concept of flexibility stretches far out of the boundaries of the single company involving the whole production network. Flexibility must be understood and taught as a mind-set to be applied to cope with turbulent conditions.

Finally, another challenge in teaching such a concept is that the word flexibility is very common in everyday language, so when students meet it in technical jargon they might have some bias as to its meaning.

METHOD

In line with the phenomenographic approach [12], this study was conducted through the notes taken during a series of interviews with the students enrolled in two specific courses that were dealing with some aspect of the focal concept analysed in this work: flexibility in manufacturing science. Both the courses had one credit equivalent (26.6 hours) of content and workload related to manufacturing flexibility. Given the different nature and purposes of the courses the topic of flexibility was presented to the students using two different approaches.

The first group attended a course in production automation [13] at KTH Royal Institute of Technology in Stockholm, Sweden (henceforth referred to as KTH). The course was held in spring 2013. There were 35 students of whom 23 took part in the interviews used in this work. The approach used in such a course was *hands-on*. The students were given tutorials on how to implement automatic operations on different kinds of machines and they were, then, assessed through laboratory activities where the teaching staff evaluated if their system was working correctly according to the given instructions. From now on in this article this group is referred as the *automation group*.

The second group attended a course in integrated production with a focus on assembly system design at KTH in autumn 2012 [14]. There were 37 students of whom 29 took part in the interviews used in this work. For this course the approach was based on direct lectures and the final examination was made of open questions. This group will, henceforth, be referred to as the *assembly group*.

The two groups of students had spent different numbers of years at the University: the automation group included students in the second year of their Bachelor's degree, while the assembly group included students in the first year of their Master's degree (typically with one and an half more years of university experience). Both groups of students were in the industrial engineering programme, so within the boundaries of such a discipline one might say that they had similar backgrounds.

After successful completion of the course, the students who agreed to participate in this study were interviewed informally. Students were free to initiate and steer the discussion, and they were only stimulated by the analyst, if required. This process only finished when an interviewee had nothing more to add and a common understanding of his or her thoughts was achieved with the interviewer. There was no structured set of questions, but the discussions focused around the following two open questions:

- What is flexibility?
- How can flexibility be beneficial for a manufacturing organisation?

Each discussion differed from the others: some focused on equipment, some on economic benefit or strategic advantages, and so on. The resulting two corresponding dimensions became the basis for implementing a matrix of perceptions, which in turn, was used to cluster the students according to their level of understanding.

The categories represent the perceptions that different clusters of people have of the phenomenon: from misconceptions by people without experience, to basic partial understanding through to the sophisticated vision of experts. The resulting clusters could, then, be arranged in a hierarchical structure known as *outcome space* of the studied concept. The consequent awareness of how people perceive such phenomenon can be used as the basis of devising strategies able to bring students to a perception that is closer to the one of people considered masterful in the specific field. Finally, it is important to note that the researchers' personal awareness of the phenomenon is left aside as in this kind of study, the only focus is that of the subjects [15].

Moreover, it is important to underline that this study has not measured the external factors influencing the learning process of each student. For example, it is quite safe to say that students who devote a higher *time on task* will reach a higher level of understanding of the topic, and that this is independent of the teaching approach. Still, the main assumption and the generative idea behind this work is that a well-designed set of teaching and learning activities, coming from a rational measure of student perception of a given topic, will contribute toward bringing students to a superior knowledge level efficiently.

RESULTS

Frame of Reference

The perception of an articulated concept such as manufacturing flexibility is necessarily a quite complex object which can be presented and understood in many different ways. For this reason, as discussed above (see Method section) in order to depict the results of this analysis, all the answers have been collapsed into two main dimensions: What is manufacturing flexibility? *When* and *Why* can manufacturing flexibility be useful for an organisation? This latter question was aimed at investigating the perceived *domain* of flexibility. The first dimension can be considered *internal* to the construct and the second *external*.

In line with the phenomenographic methodology, the reference for such analysis is the expert perception of flexibility rather than a precise definition. While the traditional ways of assessing knowledge focus on correct repetition of covered concepts, in this analysis the aim is to gather the big picture. For instance, students that cannot repeat the definition of *product flexibility* might have a better perception of the concept than students who have memorised it.

Students' Perceptions

The scrutiny of the content of the interviews has disclosed a quite broad spectrum of student perception of both the internal and external dimension. Perceptions are quite personal, but it is possible to identify common patterns in the answers that allow the students to be classified into well-defined groups. In reference to the internal dimension (*What is Flexibility?*) the clusterisation process resulted in four groups. The related aggregated perceptions can be described in order of increasing sophistication as follows. Flexibility is:

- a set of technical solutions for increasing some capability of a manufacturing organisation;
- a way of efficiently harmonising demanding product requirements with production resources in order to achieve economies of scope;
- a capability of well-designed production installation, to cope with changing conditions in different contexts;

- a mind-set that must shape the design of organisations, which find their competitive advantage in rapidly adapting and reacting to external changes.

The external dimension (which is the domain of flexibility?) is perceived in four different ways. A first, rather small, group of students believed that flexibility only affects the *production system* (1). Some students then integrated this with reference to the *product* (2). Most of the students perceived flexibility as having an impact on the *company as a whole* (3) or on part of *the network* where a given organisation does business (4).

Taxonomy of the Perceptions

The combination of the internal and external dimensions allows a complete description of the students' ways of experiencing the focal concept of flexibility to be provided. The subsequent list describes in detail the identified taxonomy, while Table 1 introduces a graphical summary of such findings:

1. *Conception 1. Simple technical*: the few students in this cluster are only able to describe some isolated technical applications of the concept. This quantitative knowledge is often not well linked to other knowledge; thus, appears rather uni-structural. They perceive flexibility as something limited to the improvement of the production system. If stimulated by the interviewer they can broaden their perspective to include the product as the main cause of the demand for flexibility. Nevertheless, it appears that their perception of the domain is limited and static: pre-structural according to the SOLO taxonomy.
2. *Conception 2. Advanced technical*: this group of students is similar to the previous one in relation to their perception of the domain. In spite of this poor understanding of the *when* and *why*, the group seems more conscious about the *what*. In particular, there is a significant difference in the way they experience the concept of flexibility. Learners in this cluster, in fact, refer to flexibility not as a fixed set of technical solutions, but they rather describe flexibility as an approach to make the production system more efficient and effective given some demanding initial conditions. The students here are implicitly aware of how flexibility enables the exploitation of economies of scope for the organisation.
3. *Conception 3. Technical economic*: this cluster is characterised by a broader perception of the domain of flexibility. In particular, the concept of economies of scope is explicitly mentioned and well-placed in the context of possible synergies between product and production system. The knowledge in this cluster is multi-structural and the learners are aware of the technical and economic limitations of most of the concept's instantiations.
4. *Conception 4. Strategic*: the students in this group have a significantly broader and most sophisticated perception of both the concept of flexibility and its domain. They showed a reliable acquisition of the quantitative knowledge and revealed personal development of such constructs into a qualitative framework. In particular, all the technical and economic aspects are known and correctly framed within the organisation as a whole. Flexibility is a global strategy to face turbulent markets, and can be implemented at any level in the organisation. The technical manufacturing solutions are correctly referred to objects in the domain of strategy. The consequent alignment of manufacturing strategy with the overall strategy of a firm is well understood and explained.
5. *Conception 5. Holistic*. The perception in the previous cluster is generally recognised as an excellent way to experience the concept of flexibility by production engineers. Nevertheless, as seen in the background to this work, from the general point of view of the whole organisation, flexibility must be understood as the driver for the development of successful companies which operate in turbulent markets. A few students clearly showed they were partially aware of this, so even if the actual courses were not aimed at directly teaching such aspects, they acquired such perceptions by integrating what they learnt with their previous knowledge.

Table 1: Summary of the students' perception of the flexibility concept and domain.

		The domain of flexibility is…			
		Production system	Product and production system	The company as a whole	The company and the network
Flexibility is…	…set of technical solutions for increasing some capability of a manufacturing organisation	Conception 1: Simple technical			
	…way of efficiently harmonising demanding product requirements with production resources in order to achieve economies of scope	Conception 2: Advanced technical	Conception 3: Technical economic		

	… capability of well-designed production installation, to cope with changing conditions in different contexts			Conception 4: Strategic	
	…mind-set that must shape the design of organisations which find their competitive advantage in rapidly adapt and react to external changes				Conception 5: Strategic holistic

Figure 1 completes the description of the survey´s results introducing the quantitative and qualitative data regarding distribution of the students across the inferred set of clusters.

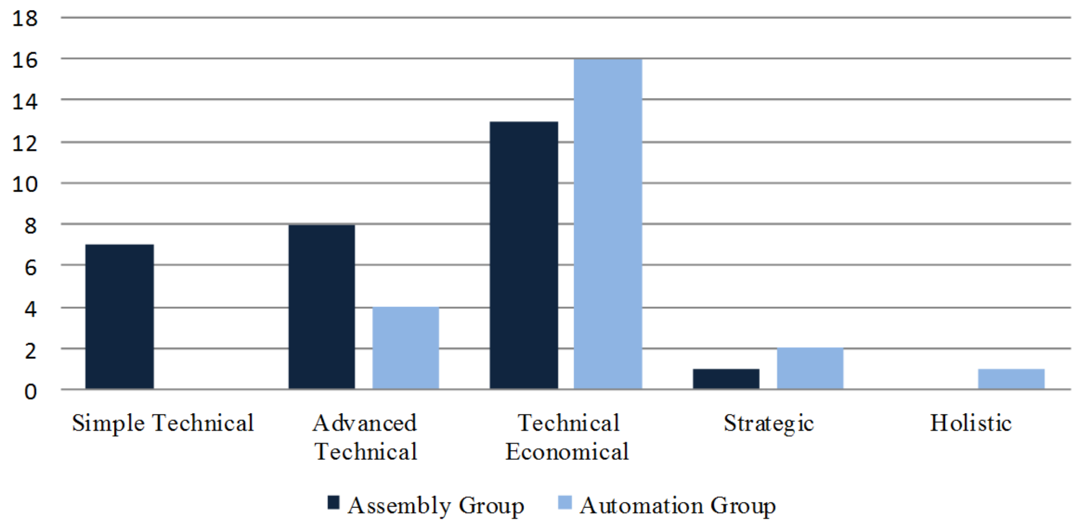

Figure 1: Distribution of the students' perception of the flexibility concept across the two focal courses.

CONCLUSION AND DISCUSSION

Flexibility is a broad topic: it is impossible to cover all the examples of it in a single course provided within the industrial domain. Consequently, when teaching flexibility, the focus should be on the basic concepts leading towards the exploitation of economies of scope at all the levels of an organisation and beyond. Nevertheless, in the engineering domain, the learning is tightly linked to real applications; thus. the courses analysed provided many examples of how flexibility is applied in industry. Students who have shown the simplest *Conception 1* are quite attached to such examples. They have not really abstracted the concept beyond these industrial installations.

Putting together such single installations through a correct understanding of the technical patterns is the gateway to the *Conception 2*. The students must be made aware that the solutions shown for increasing volume or product flexibility are based on the same principle, even if different. Well-designed lectures and stimuli from the teacher should suffice in addressing the learners to acquire this conception.

Expanding the domain from the simple production system to the combination of production system and product is the key to achieving *Conception 3*. This step is fundamental in grasping the critical concept of economies of scope in manufacturing. Exposition to different approaches to product design can enable such transition. Modular design vs integral design is an example. Examples of DF-X methods are also valid for this purpose.

Conception 4 and *Conception 5* lie in the area of qualitative knowledge. Students must engage in complex project work or in discussions that involve the strategic aspects of business to acquire such level. For example, Customer Order Decoupling Point reasoning can provide an initial framework for such a perception to be acquired. Nevertheless, the achievement of such a level can only be attained, if the students are able to relate the specific knowledge about flexibility with other knowledge in production science. Such a level must, therefore, be considered more as a programme objective rather than something acquirable within a single course.

The clear pattern depicted in the words above is represented in Figure 2, where the arrows indicate the possible patterns of evolution towards *expert-like* perception.

The average better performance of the automation group (see Figure 1) suggests that providing a series of concrete *hands-on* problems can be beneficial: traditional transmissive methods appear less effective in this field.

The inferred taxonomy is based on a solid, but limited number of interviews. The learners that participated in the survey are homogeneously distributed when it comes to previous knowledge and background: this might hide some parts of the perception spectrum. Another source of error might be that the results have been interpreted by a reduced number of analysts. In view of this, a further and broader validation of the inferred taxonomy would require more learners in different situations to be tested. Finally, it is important to note that the process of learning is complex and affected by many parameters that have been not considered in the study. Time on task and learning style among the others might have an impact on the process. A set of experiments where such parameters are controlled is therefore envisaged as necessary development towards the validation of the proposed classification.

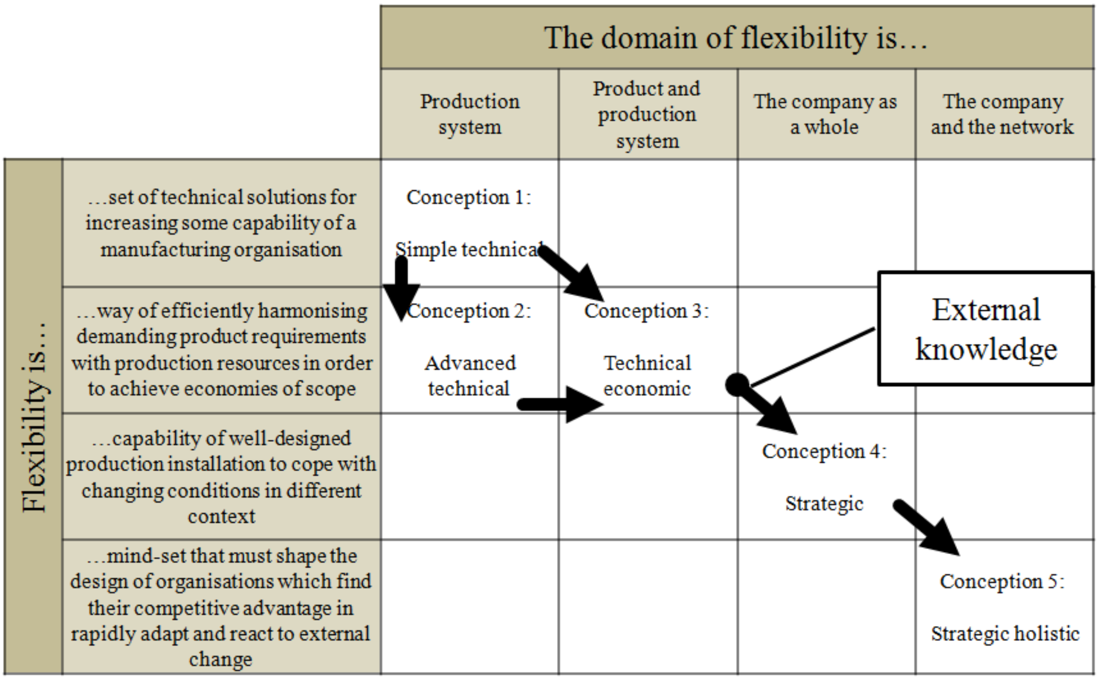

Figure 2: Summary of the envisaged evolution of the students' perception of the flexibility concept and domain.

ACKNOWLEDGEMENTS

Several organisations and people have made this work possible. First and most important is the Department of Production Engineering at KTH Royal Institute of Technology in Stockholm. Without such a good working environment it would have been impossible to produce this research. Those responsible for undergraduate and graduate studies (Lasse Wingård and Mauro Onori) have provided inspiration and financial support for this activity. The EPS group, particularly Hakan Akillioglu, provided time for data collection and organisation. Thanks to Roberto Moretti for his help in planning and structuring the interviews. A special mention must be made for the DMMS (http://dmms.iip.kth.se), and in particular, to the director Andreas Archenti, for stimulating interesting discussion in the education development.

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BIOGRAPHIES

Antonio Maffei was born in Benevento, Italy, in 1982. He received the BE and the ME degrees in industrial engineering from the University of Pisa, Tuscany, Italy, in 2004 and 2007, respectively. Antonio received a PhD degree in production engineering from KTH Royal Institute of Technology in Stockholm, Sweden, in 2012. In 2013, he started in a tenure track postdoctoral position at the Department of Production Engineering at KTH Royal Institute of Technology in Stockholm. Dr Maffei is currently Head of the *Technologies for Adaptable Production* research group. He has been active in teaching activities at the undergraduate level since 2008 and, more recently, also at the graduate level, consequently building up a strong pedagogical background. His current research interests include business models for advanced automation technology, assembly technology and engineering education. Dr Maffei is a Research Affiliate of *The International Academy for Production Engineering* (CIRP) and the Swedish Production Academy, Sweden. He was head of the Organising Committee and editor of the proceedings for the International Conference on Advanced Manufacturing Engineering and Technologies (NEWTECH 2013) held in Stockholm. He is member of the Advisory Board for the International Conference on Education, Research and Innovation (ICERI 2014) that will be held in Seville in November 2014.

Pedro Neves was born in Lisbon, Portugal, in 1986. He received the MSc degree in Electrical and Computers Engineering from the Nova University of Lisbon in 2009. In 2010, he started a PhD at KTH Royal Institute of Technology in Stockholm on the topic system evaluation and learning applied to intelligent and highly responsive production system. His current research interests include assembly technology. Since 2010, he has been participating in teaching activities at both the undergraduate and graduate levels. He is also currently a member of the Swedish Produktionsakademins doktorandnätverk PADOK, in the Svenska Produktionsakademin.

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José Barata received his PhD in Electrical Engineering from the New University of Lisbon in 1994, and he is currently a Professor at the Electrical Engineering Department where he teaches robotics, telerobotics, inteligent supervision and multiagent systems applied to the shop floor. He also a member of the Centre for Intelligent Robotics - Robotics and CIM research unit of the Uninova Institute. He has participated in many international and national projects, both as a researcher and as a local coordinator. He has participated in various projects in the area of collaborative networks/virtual organisations (Esprit PRODNET II, IST THINKcreative, VOmap, TeleCARE), projects of cooperation between European Union and Latin America, (Cimis.net, FlexSys, SCM+ and MASSYVE projects), and projects of agile shop floor (Assembly-Net network, IP EUPASS - European Ultra Precision Assembly Systems). He has acted as an expert for the European Commission as an evaluator for the NMP programme. His main areas of current research include: multiagent systems applied to the shop floor, self-organising shop floors, evolvable assembly systems, and collaborative networks/virtual enterprises/virtual organisations.