# APPLICATION OF CDIO APPROACH TO ENGINEERING BENG, MSC AND PHD PROGRAMS DESIGN AND IMPLEMENTATION

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## ABSTRACT

The paper presents the results of analyses and evaluation of the *CDIO Syllabus v2* relevance to the design of undergraduate (BEng), graduate (MSc) and postgraduate (PhD or Aspirantura in Russia) engineering programs. The analysis is based on requirements to the competencies of graduates at various higher education cycles taking into consideration the *Russian Federal State Educational Standards* (FSES) and the accreditation criteria of the *Association for Engineering Education of Russia* (AEER) harmonized with the International Engineering Alliance (*IEA) Graduate Attributes and Professional Competences* and *EUR-ACE Framework Standards and Guidelines.* The results of examination of the structure and content of the *CDIO Syllabus v2* made by the participants of the network training program “Applying the concept of CDIO in Engineering Education” developed and implemented by Tomsk Polytechnic University and the Skolkovo Institute of Science and Technology also used in the paper. It is recommended to adjust the requirements of *CDIO Syllabus v2* to learning outcomes of BEng, MSc and PhD programs graduates considering the peculiarities of complex, innovative and research engineering activity.

## KEYWORDS

Undergraduate, graduate and postgraduate engineering programs, graduate learning outcomes, accreditation criteria, Standard 2.

## INTRODUCTION

Due to the up-to-date world technological development, the division of labor in the field of engineering is becoming more complicated. It is therefore necessary to develop *tiered system of engineering education* and training of university graduates for different types of professional activity. In accordance with the Bologna process in Europe, including Russia, as well as in a number of other countries, the tiered system of higher engineering education is formed by the implementation of programs at three levels: *undergraduate (*Bachelor’s programs*), graduate (*Master’s programs*)* and *postgraduate (*PhD-programs or Aspirantura-programs in Russia*)*.

Many universities around the world use the *CDIO approach (Conceive, Design, Implement, Operate)* (E. Crawley et al, 2014) to update their Bachelor’s (Beng) programs to prepare graduates to more *complex engineering activities* at all stages of the life cycle of technical objects, processes and systems. This approach is widely used, as it is consistent with the requirements of international standards (*IAE Graduate Attributes and Professional Competences*) to the engineering HEI's graduate learning outcomes and competences of professional engineers (www.ieagreements.org/IEA-Grad-Attr-Prof-Competencies.pdf). The *CDIO* approach allows the design and implementation of BEng programs as a basic engineering education in accordance with the criteria for accreditation of engineering programs in the countries - signatories of the *Washington Accord*, including the accreditation criteria of the Association for Engineering Education of Russia (AEER) (A. Chuchalin, 2012).

Master's (MSc) programs in engineering in accordance with the AEER accreditation criteria, harmonized with *EUR-ACE Framework Standards and Guidelines*, generally orient graduates towards *innovative engineering activities* (www.enaee.eu/eur-ace-system/eur-ace-framework-standards). Russian postgraduate programs (Aspirantura) as required by Federal State Educational Standards (FSES) focus mainly on preparing graduates for *research activities* in the field of engineering sciences. The report of the *«Quality Assurance in Doctoral Education - results of the ARDE project»,* carried out by the European University Association *(EUA),* contains similar recommendations for the *PhD* – programs (*J. Byrne et al.* 2013).

It should be noted that Bachelor's are involved in complex engineering activities at the *Conceiving* and *Designing* stages of technical objects, processes and systems. However, in practice, BEng program graduates are more often involved in the *Implementing* and *Operating* of products and systems. Innovative activities of MSc program graduates are often concerned with the *Design* of new engineering products or systems. Research activities of PhD–program graduates mainly aim at creating a scientific basis for the development of innovative products and systems at the *Conceive* stage. However, Masters and PhD-holders may also participate in the *Operating* and *Implementing* of engineering products and systems.

The Systems approach to the design of engineering education at the Master's and PhD – levels, similar to the CDIO approach to the basic engineering education at the Bachelor's level, is still in its early stages of development. At the same time, it is important for research universities, such as Tomsk Polytechnic University, the Skolkovo Institute of Science and Technology and others to develop guidelines similar to *CDIO Standards* and *CDIO Syllabus* to improve the quality of educational programs in engineering and technology at Master's and PhD levels. The advantage of the *CDIO Syllabus* is that in contrast to the accreditation criteria, the *CDIO Syllabus* requirements are more detailed and are comfortable to use in the curriculum design process. At the Skolkovo Institute of Science and Technology, a special Learning Outcomes Framework has been developed for the design of graduate and postgraduate programs focused on research and innovation (E. Crawley et al. 2013). The Framework is an extension of the CDIO syllabus v2 but does not take into account peculiarities of intended learning outcomes for MSc and PhD-program graduates related to the peculiarities of their future professional activities.

Currently, for the design of undergraduate engineering programs, the *CDIO* approach recommends the learning outcomes presented in the *CDIO Syllabus v2* (Crawley, E.F. et al. 2011). *The* structure, content and implementation technology of educational programs depend on the intended learning outcomes. Thus, the structure and content of the learning outcomes presented in the *CDIO Syllabus* are the system-forming factors in the design of engineering programs.

All learning outcomes presented in the *CDIO Syllabus v2* are relevant to BEng programs focused primarily on the preparation of graduates for complex engineering activities. However, the degree of their relevance is different, which is reflected in the structure and content of engineering programs. The degree of relevance of *CDIO Syllabus v2* sections and items for MSc programs and PhD-programs may differ significantly from the degree of their relevance to BEng programs as they are intended for training of graduates for other types of activities (research and innovation).

The authors of the second edition of the book *«Rethinking Engineering Education, the CDIO Approach» (Springer*, 2014) indicate the fundamental possibility of adapting the *CDIO* approach to the development of Master's and *PhD*-programs (E. Crawley et al, 2014). However, they do not give recommendations on how to adapt the *CDIO Standards* and *CDIO Syllabus* to a tiered system of engineering education taking into account the differences between intended learning outcomes for BEng, MSc and PhD-programs related to the differences between prioritized professional activities of their graduates.

This paper is an attempt to further analyze and evaluate the relevance of the *CDIO Syllabus v2* to design educational programs for undergraduate, graduate and postgraduate studies in engineering and technology. The analysis is based on different requirements to the competencies of graduates at various higher education cycles for complex, innovative and research activities. Integration and systematization of the requirements of the Russian FSES and AEER accreditation criteria harmonized with the *IAE Graduate Attributes and Professional Competences* and *EUR-ACE Framework Standards and Guidelines* define the requirements to the competencies of BEng, MSc and Aspirantura (PhD) program graduates. The results of the examination of the structure and content of *CDIO Syllabus v2* made by the participants of the network training program "Applying the concept of CDIO in Engineering Education" developed and implemented by Tomsk Polytechnic University and the Skolkovo Institute of Science and Technology (A. Chuchalin, 2015) are also used in the paper. Representatives of 15 universities from Russia and the CIS countries took part in the study.

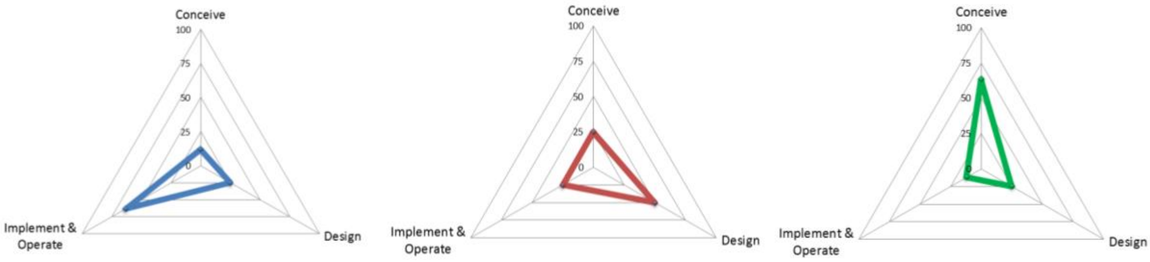
## TYPES OF ENGINEERING ACTIVITIES AND COMPETENCIES OF GRADUATES

As mentioned above, the graduates of BEng programs are mainly trained for complex engineering activities: Conceive, Design, Implement and Operate technical objects, systems and processes, solving a wide variety of technical and other issues at all stages of the engineering product life cycle. Solving complex engineering problems requires *basic* knowledge of mathematics, natural sciences, engineering and other sciences, as well as specific technical, economic, administrative and other knowledge, including interdisciplinary knowledge in the area of specialization.

Analysis of Federal State Educational Standard and AEER criteria shows that most core competencies of Bachelor's (>60%) corresponding to AEER accreditation criteria, are related to complex engineering activities at the stages of *Implementation & Operation* of technical objects, processes and systems. About 25% of the intended learning outcomes are focused on *Design*, and a little more than 10% of competencies enable Bachelor's to participate in activities at the *Conceive* stage. This structure of competencies defines the prioritized area of s' professional activities (Figure 1, a).

Masters are prepared mainly for innovative engineering activities aimed at the development and design of new technical products, systems and technologies for human needs to get social and (or) economic impact, and therefore demanded and competitive. Innovative engineering is an interdisciplinary activity. It requires *deep* fundamental and applied knowledge, based on the analysis and synthesis of technical objects, systems and processes with the use of mathematical models of the high level with more emphasis on Interdisciplinary knowledge.

Half of the master's learning outcomes (50%) corresponding to the AEER accreditation criteria are related to *Design*, 25% are focused on *Implement & Operate*, and 25% of competencies enable Masters level graduates to participate in activities at the *Conceive* stage. This structure determines the scope of the Master's graduate main professional activities (Figure 1, b).




a) b) c)

Figure 1. The areas of prioritized engineering activity
of Bachelor's, Masters and PhD-holders

The PhD-program graduates are prepared mainly for *research activity* in the field of *engineering sciences*. It aims to *generate* new knowledge and to transform fundamental knowledge into applied knowledge for its subsequent use in engineering, as well as scientific support of the development of new technical products, systems and technologies based on research results.

In the draft of new Russian Aspirantura FSES for the area "Engineering, technology and technical sciences" the majority (>60%) of expected graduate competencies is connected with the preparation for research activities at the stage of *Conceive*, 25% of learning outcomes focus on activities at the stage of *Design*, and a little more than 10% of competencies refer to *Implement & Operate* stages. This structure of competencies defines the area of prioritized activities of Aspirantura (PhD)-program graduates (Figure 1, c).

## APPLICABILITY OF *CDIO SYLLABUS V2* ITEMS FOR BENG, MSC AND PHD-PROGRAMS

A group of experts from leading Russian universities was asked to assess the applicability of *CDIO Syllabus v2* items. Figure 2 shows the results of expert assessment of the grade of applicability of the *CDIO Syllabus v2* items, as factors for planning learning outcomes of Bachelor's, Master's and PhD-programs in engineering and technology. The grade of the *CDIO Syllabus v2* items applicability is evaluated by 4 - point scale: 1 - low, 2 - medium, 3 - high, 4 - very high.

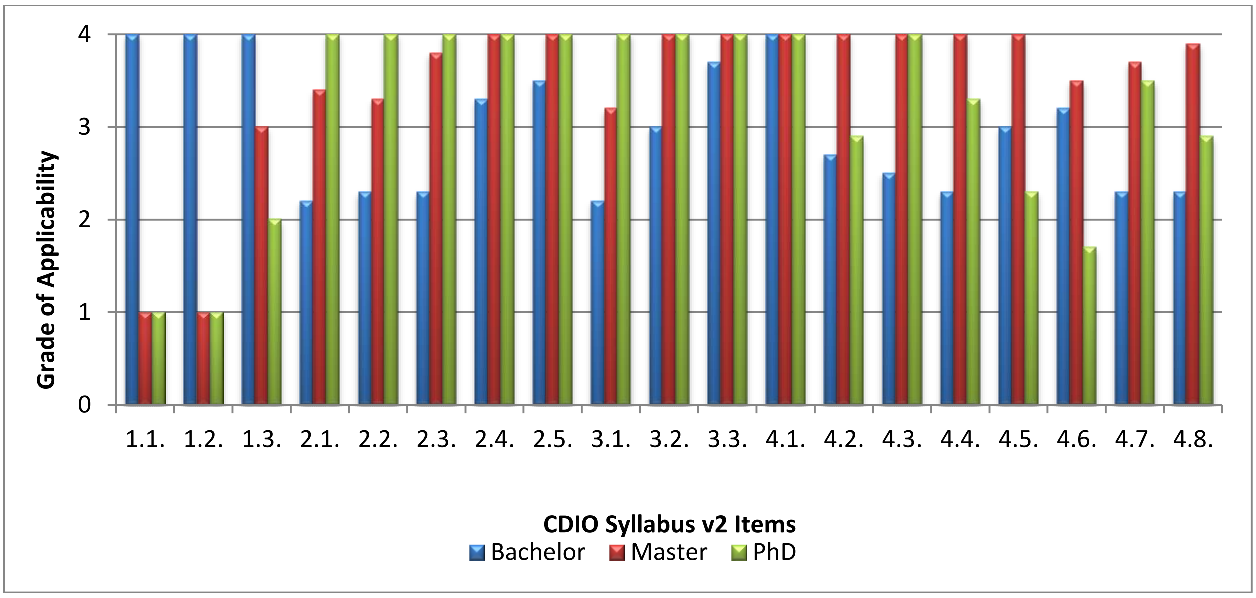



Figure 2. The level of applicability of the *CDIO Syllabus v2* items for planning learning outcomes for Bachelor's, Master's and PhD-program graduates

The explanatory comments to the results of the expert evaluation of topics of the *CDIO Syllabus v2* sections and items for planning learning outcomes for Bachelor's, Master's and PhD-program graduates are as follows.

## SECTION 1 OF *CDIO SYLLABUS V2*

*"Knowledge of underlying mathematics and sciences"* (Item 1.1), "Core engineering fundamental knowledge*"* (Item 1.2), as well as "Advanced engineering fundamental knowledge, *methods and tools"* (Item 1.3) corresponding to the field and specialization of training are necessary for complex engineering activities. This knowledge should be fully acquired within undergraduate educational programs. The AEER accreditation criteria require that at least a quarter of scientific and educational resources of a program (60 out of 240 *ECTS* credits of a 4-year Bachelor's programs) should be provided to the study of mathematics and natural sciences.

The advanced natural science and mathematical training necessary for innovative engineering activities in a relevant field to be carried out at the Master's level (AEER criteria recommend up to 15 of the 120 *ECTS* credits of 2-year Master's programs). The study of advanced methods and tools for engineering activities related to the specialization is also possible. However, far fewer resources are required for this in MSc programs than at the BEng level. Development of the competence to generate new scientific knowledge, the level of which significantly exceeds the level of basic knowledge, is a task of training for PhD-program graduates. Therefore, scientific and educational resources on assimilation of ready-to-use knowledge should be limited in PhD-programs.

Thus, for the design of engineering programs at the MSc and PhD levels, it is necessary to adapt Items 1.1 and 1.2 the *CDIO Syllabus v2* to the requirements of preparing graduates for innovation and research activities. It is felt that some focus must be given to interdisciplinary knowledge to broaden the perspective of graduates and post-graduates. Some specific knowledge in the processes of innovation should also be considered. It is advisable to specify the wording of Item 1.3 of the *CDIO Syllabus v2* for different higher engineering education levels, taking into account the intended learning outcomes.

## SECTION 2 OF *CDIO SYLLABUS V2*

*“Analytical reasoning and problem solving”* (Item 2.1), especially in the “Formulation, analysis and evaluation of the problems in the face of uncertainty”, as well as making recommendations to address them, refer to the competencies of graduates of MSc and PhD studies to a greater extent. These competencies are especially important for innovation and research engineering activities. BEng program graduates deal to a lesser extent with pure analytical work. However, in the course of complex engineering activities, they can use the models of technical objects, processes and systems that have been developed by graduates of MSc and PhD-programs. It is necessary to consider this in the design of appropriate educational programs.

*“Experimentation, investigation and knowledge discovery”* (Item 2.2) is more typical for graduates of MSc and PhD-programs engaged in innovation and research engineering activities. This is especially true for the topic of formulating, testing and defense of hypotheses. It applies to a lesser extent to the search for information using print and electronic media, where BEng program graduates can also be engaged in the process of complex engineering activities.

*“System thinking”* (Item 2.3) necessary to evaluate and find a balanced solution to various problems in determining the priorities and reaching trade-offs in innovation and research engineering activity is required from MSc program graduates and PhD-holders to a greater extent than from BEng program graduates. System thinking is also necessary for ,s to be able to understand the conditions of occurrence of systems and the ability to organize system interactions in the process of complex engineering activities. However, more attention should be given to the formation in system thinking for graduates in MSc and PhD programs than in BEng programs.

The expert assessment shows that initiative, decision-making, perseverance in achieving goals, creative and critical thinking, time and resources management are almost equally required from Bachelor’s, Master’s and PhD-programs graduates. Engineering specialists of all categories, each at their own level of engineering activity should be aware of the importance of self-education and lifelong learning, integration of knowledge and formation of *“Personal attitude, thought and learning”*.

Graduates of BEng, MSc and PhD-programs must demonstrate truthfulness, social responsibility and commitment to professional ethics. They should be able to perceive the adversity in modern relationships in the world of engineering and technology with confidence, loyalty and in an impartial manner, have a personal vision and intention in life and professional courtesy. All this defines “*Ethics, equity and responsibility”* (Item 2.5) of each engineering specialist in his/her workplace.

Thus, according to expert assessment, Items 2.1, 2.2 and 2.3 of the *CDIO Syllabus v2* are more relevant for the design of MSc and PhD-programs than for BEng program design. This should be considered in the distribution of scientific and educational resources of corresponding programs. It is advisable to adapt the wording of Items 2.1, 2.2 and 2.3 of the *CDIO Syllabus v2* for various higher engineering education levels. The urgency of the requirements in preparing Bachelor’s, Masters and PhD-holders to complex, innovative and research engineering activities in Items 2.4 and 2.5 of the *CDIO Syllabus v2* is almost identical. This should be considered when designing engineering programs at all levels.

## SECTION 3 OF *CDIO SYLLABUS V2*

"Expertise in *teamwork"* (Item 3.1) and "*Communications"* (Item 3.2), including "C*ommunication in foreign languages"* (Item 3.3) is important for any kind of engineering activity. According to expert assessment, Bachelor's, Masters and PhD-holders must be almost equally able to develop a communication strategy, possess writing and speaking skills, carry on a dialogue, use graphic and electronic media, establish communication and build up networking. The AEER accreditation criteria recommend 20 - 30 credits of humanities and economic sciences in BEng programs within the 240 *ECTS* credits of 4-year programs. However, such abilities as negotiation, compromise, conflict resolution, formation of effective team, leadership, team management and team development are mostly required from Master's and PhD-program graduates. The particular relevance of Item 3.1 and a number of components of Item 3.2 of the *CDIO Syllabus v2* should be reflected in the structure of the scientific and educational resources of Master's and PhD-programs to prepare graduates for innovation and research in engineering and technology.

## SECTION 4 OF *CDIO SYLLABUS V2*

Understanding the "*Social and environmental context"* of engineering activities (Item 4.1) is a requirement to all categories of specialists in the field of engineering. It is important to understand contemporary issues and values of the human civilization, its historic role and the responsibilities of the engineer, the cultural aspects of engineering, the impact of engineering on society and environment and the need for sustainable development and the global perspectives.

As a part of "*Enterprise and business context"* (Item 4.2) graduates of engineering programs at all levels need skills to work in organizations, experience in engineering entrepreneurship, ability to use new technologies for the development and evaluation of professional activities. Work experience in international organizations engaged in innovation and research activities, ability to evaluate the interest of various stakeholders, defining goals and strategy considering economic and financial aspects of engineering design are particularly necessary for graduates of Master's and PhD-programs. This should be taken into account during the formation of scientific and educational resources of corresponding programs.

Experience in "*Conceiving, system engineering and management"* (Item 4.3) and "*Designing"* (Item 4.4) of technical objects, processes and systems is more important for Masters and PhD-holders than for Bachelor's. In the area of '*Implementing"* (Item 4.5), the ability to design sustainable manufacturing processes, the system integration of technology and software products, as well as production management are the most important topics for graduates of MSc programs. According to the expert assessment, the graduates of BEng programs need skills in the production, testing, verification, validation and certification of end products. Production skills are not very relevant to PhD-holders. The difference in training specificity needs to be reflected in the distribution of scientific and educational resources within engineering programs at various levels.

According to the expert assessment, skills and experience in "*Operation"* (Item 4.6) of technical objects, processes and systems are important for BEng and MSc program graduates. The skills in the design and optimization, the sustainability and product safety, the experience in how to operate technical products and their systematic improvement and evolution are most important for Masters graduates. The most relevant skills for Bachelor's who are actively involved in complex engineering activities are the following: supporting the system life cycle, including decommissioning and disposal of products with the determination of the impact on the environment. Preparation for most of the stages of the production operations is not highly relevant to PhD-holders except their possible participation in the process of system improvement and evolution of engineering products. A significant difference in the degree of applicability of competencies of Bachelor's, Masters and PhD-holders in the use of the skills of engineering for product operation should be taken into account in the design of appropriate educational programs.

Competencies in the "*Leading engineering endeavors"* (Item 4.7) are essential for high-level specialists involved in innovation and research activities. The ability to identify a paradox, thinking creatively and visioning of high-level solutions, leadership skills in the organization and beyond, are most important for PhD-holders. The ability of thinking creatively and visioning of high-level of solutions are also important for MSc program graduates. However, preparing for innovation in terms of development and defense of projects, project planning and management, control over their implementation until completion is even more important for Masters rather than for PhD-holders. All of the components of leadership competencies in engineering enterprises are a priority for Master's and PhD-program graduates. According to the expert assessment, they are likely to be less required for BEng program graduates in the course of complex engineering activities. It is advisable to consider these peculiarities during the design of educational programs.

The ability for "*Engineering entrepreneurship"* (Item 4.8) is obviously mostly manifested in innovative engineering. Therefore, adequate scientific and educational resources aimed at developing an entrepreneurial culture should become a significant part of MSc programs. The recommended volume for entrepreneurial and innovation activity is at least 30 credits within the 120 *ECTS* credits for 2-year Master's programs according to AEER accreditation criteria. However, for complex engineering situations, Bachelor's can also participate in entrepreneurial activity, creating enterprises and develop innovative product marketing. They may also require entrepreneurship skills in knowledge-intensive business planning, production and services design using new technologies, development of a new innovation system and new engineering processes, creation of an innovation infrastructure and, in particular, management of the intellectual property. Varying degrees of applicability of Section 4 items of the *CDIO Syllabus v2*, related to social, environmental, entrepreneurial and business context of complex, innovative and research engineering activity should be considered when designing engineering programs of Bachelor's, Master's and PhD-studies through the appropriate distribution of scientific and educational resources. When designing the structure and content, as well as considering the technologies for program implementation at various levels, it is necessary to provide resources adequate for priorities in the formation of certain competencies for the planning, systems engineering and management, as well as the design, implementation and operation of technical objects, processes and systems at different levels.

## CONCLUSION

In order to use the *CDIO* approach for the design of tiered engineering programs in order to improve their quality, it is necessary to adjust the content of the *CDIO Syllabus v2* to the learning outcomes of BEng, MSc and PhD-programs, considering the peculiarities of complex, innovative and research engineering activities. It is possible to improve the structure, content and implementation technologies of tiered engineering educational programs based on the CDIO Syllabus, adapted to the training of specialists in the field of engineering and technology for various types of activities. It is important to distribute the scientific and educational resources of BEng, MSc and PhD-programs for the effective achievement of the intended learning outcomes. It is also appropriate to update the *CDIO Standards*, defining the requirements for educational programs at various levels in the context of specific engineering activities, including the requirements of the curriculum, the learning environment, the learning technologies, the professional qualifications of teachers and the methods of evaluation of programs and the particular graduate learning outcomes.

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