International Journal of Engineering Education Vol. 33, No. 4, pp. 1233–1241, 2017
Printed in Great Britain

0949-149X/91 $3.00+0.00

Implementation and Deployment of Transdisciplinary Learning Environments during Short-term Educational Events on Computational Science*

KLAVDIYA BOCHENINA[1],** ANNA BILYATDINOVA[1], ALEXEY DUKHANOV[1] and GERASSIMOS ATHANASSOULIS[2]
[1] eScience Research Institute, ITMO University, 49 Kronverksky Pr. St. Petersburg, 197101, Russia.
[2] School of Naval Architecture and Marine Engineering, National Technical University of Athens, 9, Heroon Polytechniou Street, Zographos 157 73, Athens, Greece.
E-mail: k.bochenina@gmail.com, a.bilyatdinova@gmail.com, dukhanov@corp.ifmo.ru, mathan@central.ntua.gr

Short-term educational events having the duration from several days to several weeks bring together participants from different educational institutions with diverse backgrounds and provide a unique opportunity to foster their collaborative competencies beyond a familiar environment. In this paper, we consider a short-term event as a basis for deployment of Transdisciplinary Learning Environment (TLE) intended to familiarize participants with how to solve multi-domain ill-defined problems in groups. Summarizing our experience in organizing several Russian and international Schools in Computational Science with more than 200 participants over 2008–2016 years, we introduce the principles of short-term TLE design and deployment and describe knowledge transfer processes which take place in them. The objective of the paper is to present and discuss the results obtained during the implementation of short-term TLEs for students in Computational Science and to create a basis for purposeful formation of learning environments aimed at mastery of transdisciplinary competencies of engineering students. The main conclusions from the study are as follows: (i) groups of participants with different background can cope with transdisciplinary problem after being immersed into TLE, (ii) consequence of activities during team work corresponds to those in the proposed knowledge transfer cycle, (iii) previous research experience of participants influences their flexibility in the choice of an area during a short-term team work.

Keywords: knowledge transfer; transdisciplinarity; short-term educational programs; learning environments; computer engineering education

1. Introduction and related work

Knowledge society is characterized by continuous diversification of research fields resulting in a growth of interdisciplinary research [1]. Actually, the creation of new knowledge by the investigators with different areas of study is considered in the framework of several concepts including multi-, inter- and transdisciplinarity. The difference between them is usually determined by a level of cross-fertilization among the disciplines [2, 3]: from studying the problem by several experts separately to transgressing the boundaries of individual subjects resulting in a holistic outcome. In the study we use the term 'transdisciplinarity' to underline the following distinctive features of learning environments that we are aimed to deploy: (i) creation of shared knowledge field rather than combination of individual efforts; (ii) focus on synergetic interactions between the disciplines while solving real-world problems; (iii) going beyond a 'comfort zone' of narrow specializations and occupational roles, and (iv) a complexity [4] as an essential property of studied systems.

Engineering education is called upon to meet the challenges of the training of specialists who are ready to perceive transdisciplinary problem statements. This is especially important for experts in information-communication technologies (ICT), which serves as a binding basis for a variety of subject areas. For example, during the development of high-tech or scientific software an engineer should work closely with the researchers or domain experts from different areas and perceive diverse information at a high level of abstraction. Skills of working in heterogeneous, multi-domain teams are also important for specialists from other engineering disciplines due to the growing spread of inter- and transdisciplinary problems. In general, the skills of effective teamwork are highly desirable for employees [5].

The list of specific transdisciplinary competencies [6] includes the ability to work effectively with experts of different majors, to create an integral vision of a complex problem and to generate a solution at the intersection of several subject fields. Although issues of inter- and transdisciplinary education have been raised for a long time (e.g. [7]), even now there is a shortage of educational methods and techniques to facilitate a mastery of

** Corresponding author.

* Accepted 18 February 2017.

corresponding skills. The difficulty is that the efficiency of collaborative projects is mainly based on the transfer of tacit knowledge [8] which is impossible to convey in a formalized manner.

Most of the studies about transdisciplinary education address long-term (as graduate programs) or mid-term (as particular courses) activities. In [9] authors propose a transdisciplinary engineering research and education model which combines core and supplementary courses with team projects. Authors of [10] and [11] describe a framework for STEM graduate education to develop transdisciplinary competencies and mindsets on the basis of sociotechnical communities. Domik and Fischer in [12] propose two innovative teaching and learning strategies for transdisciplinary education. Hyun [13] investigates the transformation of degree programs to infuse the transdisciplinary research into the curriculum. Aneas [14] considers the challenges of implementation of transdisciplinary approach in technical universities and the possible strategies to face them. Steiner and Kanai [15] present a methodology for assignment of students to multidisciplinary projects and teams and study the impact of different factors on team effectiveness. In contrast, we are focused on providing initial first-step experience of participation in transdisciplinary projects to engineering students in the course of short-term events.

A wide body of research considers transdisciplinarity through the prism of knowledge management (e.g., authors of [16] study the convergence between the knowledge management and transdisciplinary research). The knowledge transfer between members of a newly created transdisciplinary team is complicated by knowledge barriers [17] specific to multidisciplinary collaboration (e.g. using different mathematical foundations). Godemann in [18] investigates the key factors of effective knowledge integration process among members of a transdisciplinary team including common knowledge bases and mental models. Axelsson in [19] proposes a normative model for transdisciplinary knowledge production which also includes a stage of development of a common framework for research. In this study, we consider how to establish short-term learning environment in order to support knowledge transfer between students with different specializations.

The rest of the paper is organized as follows. In Sections 2 and 3, we describe organizational and methodological basics of fast deployment of learning environments meant to exchange of experiences and ideas between engineering students with various majors. We propose a scheme of knowledge transfer to describe the process of creation, growth and dissemination of knowledge during short-term educational events. In Section 4 we discuss our experience of preparation and staging short-term educational programs in Computational Science (CPS), and the results of the application of proposed approach. In general, the ideas at the heart of this work can be expanded to supplement mid-term and long-term educational programs with activities to improve transdisciplinary skills of engineering students.

2. Concepts of short-term transdisciplinary learning environments

Short-term educational programs such as summer schools and conferences of young scientists are the most common way to bring together students from different institutions of higher education to upgrade their skills in a particular knowledge area. In contrast with long-term programs, short-term events usually gather the participants with diverse experience and skills representing various research and professional communities [20]. Along with time restrictions of these events, these conditions are well suited to transdisciplinary education. The latter explains our motivation to develop a framework for design and deployment of TLEs on the basis of short-term educational programs. By transdisciplinary learning environment, we mean a learning environment aimed at fostering transdisciplinary competencies [6]. This aim reflects the principal difference between short-term TLE and traditional short-term courses: while the latter are mostly oriented to the transfer of codified knowledge in frames of predefined subjects, the former focuses on a co-creation of new knowledge beyond the borders of individual disciplines. The following principles of TLE's design are based on the experience accumulated to date in organizing annual spring schools in High-Performance Computing (since 2008, [21]) for Russian students and international Young Scientists Conference (since 2012, [22]).

2.1 Principles of short-term TLE design

We formalized principles, goals and activities of short-term TLE building on four principles of educational framework according to [23], namely, the role of context (A), the role of content (B), the role of facilitation (C) and the role of assessment (D). In our opinion, the most natural and effective way to foster transdisciplinary competencies is to simulate the process of formation of shared knowledge field by repeating the main stages of knowledge co-creation while working on a complex problem. This together with principles A-D determines the underlying goals of a short-term TLE:

(1) provide the common conceptual framework as a basis of collaborative activities—A, B;
(2) maintain and intensify the process of purposeful interchange of experience and ideas between participants with different roles, majors, research and educational background—A, C;
(3) give the students the practically-based understanding of transdisciplinarity via group solving of ill-defined cross-disciplinary problems—A, B;
(4) assess the outcomes of the participants—D;
(5) provide organizational and technical support of short-term event—C.

These goals, in turn, determine the main activities performed in the frames of TLE and interdependences of these activities shown in Fig. 1 (numbers above the rectangles denote corresponding goals).

The first goal of TLE (creation of shared conceptual framework) is implemented during traditional educational activities such as lectures and master classes. In relation to TLE, they are aimed not only to get the facts across to the participants but also to prepare the ground for their further collaboration. Social activities (goal 2) are aimed to encourage the creation of a network of both formal and informal interconnections between the students. Transdisciplinary (TD) activities (goal 3) usually assume collaborative work on group projects focusing on the problem which requires synergetic interactions between the participants under strict time restrictions. The results of collaborative work are assessed (goal 4) by a panel of experts, and the best works are awarded. The scheme in Fig. 1 underlines the fact that the statement of a problem and quality criteria could be corrected after an initial assessment of participants' knowledge and skills. Proposed two-stage assessment allows the organizers: (i) to tune the complexity of a problem according to students' capabilities, (ii) to carry out the formation of teams based on the results of preliminary testing, and (iii) to evaluate the results of team work.

2.2 *Scheduling and deployment of short-term TLE*

Effective curriculum design is a crucial aspect of student engagement (see e.g. [24]) so the need to a purposeful formation of event's schedule cannot be underestimated. All activities in frames of short-term TLE could be divided into three types: (i) preliminary activities before the beginning of the event, (ii) scheduled activities which are reflected in the agenda of the event, (iii) support activities which are out of the schedule but have to be performed during TLE lifecycle. Fig. 2 represents scheme of TLE deployment on the basis of short-term educational event. The lower part of Fig. 2 illustrates the approximate timeline of an event. Three rows of a schedule represent social, educational and transdisciplinary activities, respectively.

First of all, organizers provide an extended explanation of aims and scope of the event to the participants. During a special session just after the opening, participants have to get acquainted and learn about each other's specializations. In parallel, organizers ask the participants to fill in the form to estimate their qualifications in different subject

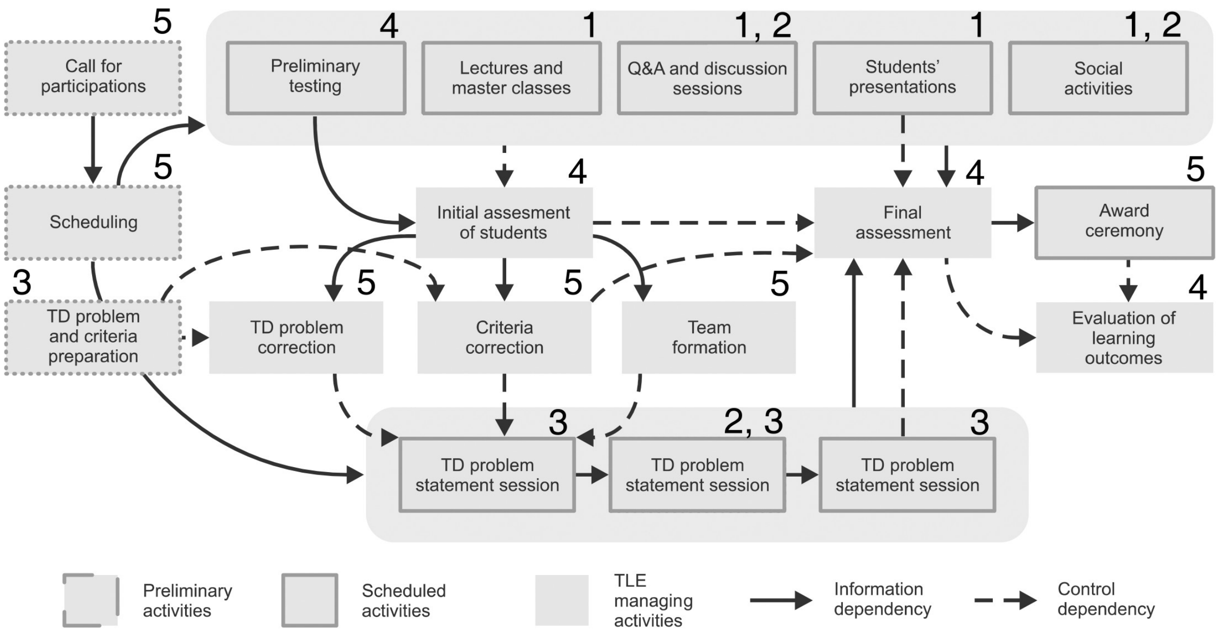

Fig. 1. The scheme of short-term transdisciplinary learning environment.

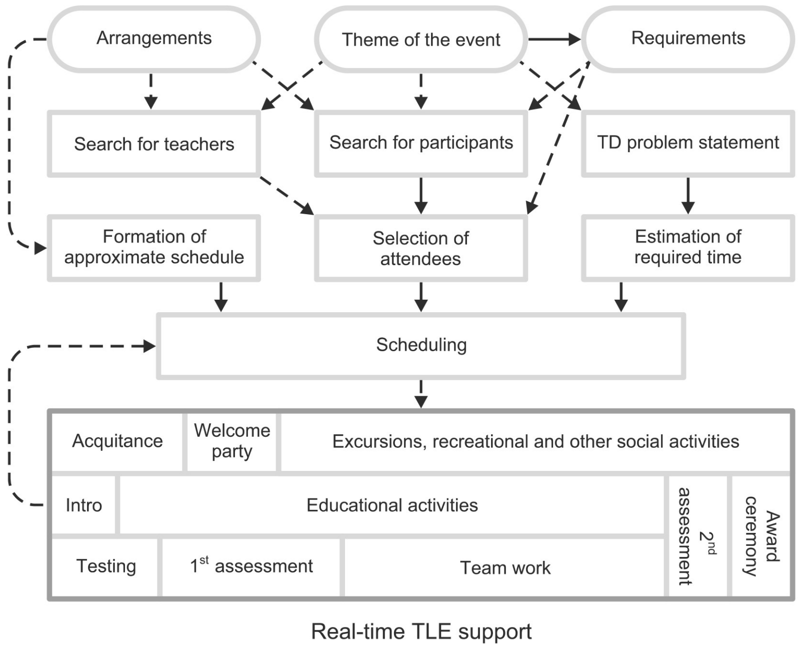

Fig. 2. The scheme of deployment of short-term TLE.

areas. The results are processed before the beginning of team work. This time slot has a two-fold purpose. Firstly, it is aimed to create a common conceptual framework during lectures, master classes, discussion sessions, and scientific presentations. Secondly, it is used by educators to group out the participants based on the results of testing and to correct the formulation of the problem if necessary. Team work is usually performed during several sessions on the same days as other educational activities. The evaluation of the results of team work is performed during final assessment.

3. Knowledge transfer in short-term TLEs

TLE has the same components as a traditional learning environment in higher education [25, 26]—it combines resources, people, and contexts in a process of purposeful formation of competencies. The main distinguishing feature of transdisciplinary LE is its orientation to a transfer of tacit [8] rather than codified knowledge. To achieve this goal in frames of short-term TLE, we supplement the step of knowledge acquisition (which is common for short-term events) with steps of creation, use and transformation of knowledge thereby realizing full cycle of knowledge transfer. The scheme of knowledge transfer in short-term TLE is depicted in Fig. 3. This scheme is a result of development of a more general scheme proposed in [27] as applied to short-term TLE.

In general, knowledge transfer cycle (KTC) is organized as a spiral with four different stages (formation of a community, knowledge accumulation, knowledge production and knowledge spreading) repeated on two levels (individual and team). In addition, knowledge and skills from the individual level are the basics for such stages on the team level (it is represented by dashed arrows). The first part of KTC (individual level) is primarily aimed to prepare a common ground of knowledge by lectures and master classes and to create a network of informal links between students. The stage of knowledge production at the individual level is external due to time restrictions of the event. We recommend including individual presentations of students (highlighting current state of their theses of research) to the scheduled activities of the event. These presentations serve both as an activity to develop soft skills and as a way to familiarize students with each other's specializations.

During group work, students repeat the four stages of knowledge transfer process on a team level while working of a transdisciplinary problem. Its required properties are the following:

(1) A problem should not have only one feasible solution (in other words we require it to be ill-defined). Participants are encouraged to develop, to compare and possibly to combine various solutions (e.g., if they consider a problem at different scales);
(2) A problem is related to the concept of complexity. This property reflects the intimate link between transdisciplinarity and complexity which was introduced and discussed in details in studies of Nicolescu [28, 29].

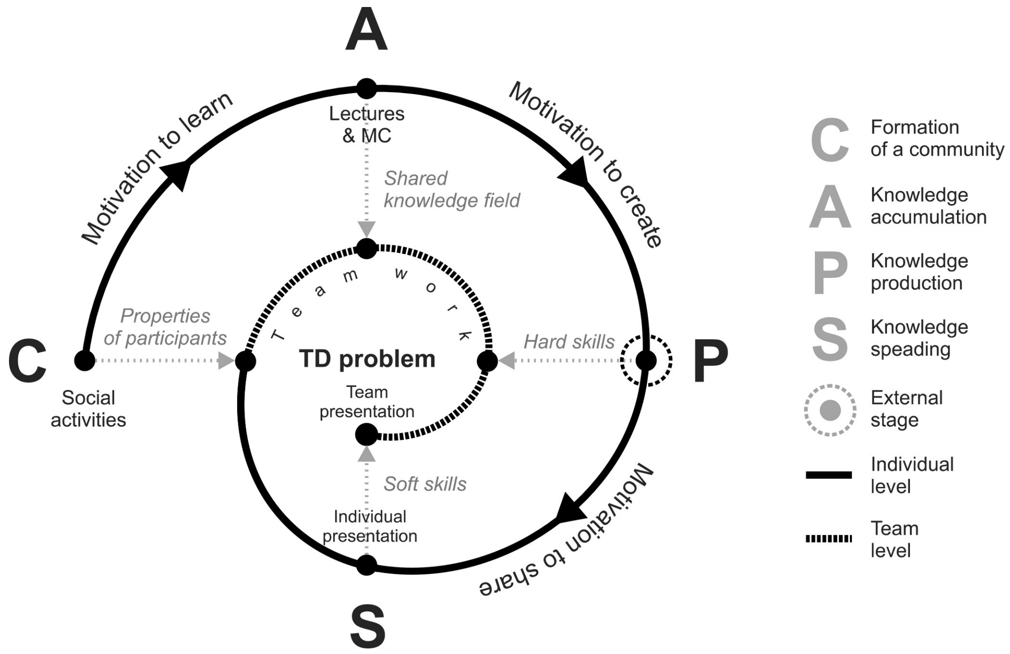

Fig. 3. Knowledge transfer cycle in a short-term TLE.

(3) A problem requires a choice of a particular task to be done by participants themselves.
(4) A problem lays at the intersection of different subjects and requires the application of both hard and soft skills of students. At the same time, the choice of particular disciplines, methods, responsibilities and ways of interactions is provided to the students.

The results of team work are estimated by a group of experts during team presentations' session. These criteria can include: (i) completeness of consideration of a studied problem; (ii) justification of applied methods and techniques; (iii) practical applicability of offered solution; (iv) quality of presentation; (v) Q&A session. To assess how the skills of individual participants improved during the event, a method described in [30] can be applied. The core of the method rests on measuring changes in skills of participants for different subject fields before and after the event.

4. Results and discussion

Proposed methods of planning, scheduling, deployment, maintenance and facilitating knowledge transfer in the course of short-term TLE were primarily inspired by a rethinking of our experience in managing short-term educational events on Computational Science. In 2008, eScience Research Institute of ITMO University hosted the Annual Scientific School 'Technologies of High-Performance Computing and Computing Simulation' for the first time. From 2008 up to the present time this nationwide one-week school takes place every April in Saint Petersburg. Over the years, more than 200 Russian bachelors, graduates, and postgraduates participated in the activities of the School. In average, each one-week School gathers 35 participants from 20 organizations located in 10 different cities. Schools are oriented to senior students, graduates and post-graduates in Computer Science whose interests are related to modeling and simulation. Participation in School is completely free, and the best scientific reports are awarded diplomas and valuable prizes. From 2012 to present, each School has a sub-topic representing a particular aspect of Computational Science to be studied in detail, for instance, in 2012 'Virtual Reality Technologies', in 2013 'eScience Technologies', in 2014 'In the World of BigData', in 2015 'A Study of Global Systems', and in 2016 'Computational Technologies for Decision Support'.

Our successful experience at the nationwide level and the growing interest of the global community to the scientific education in CPS led to the transition of these events to the international level. In 2012 the first International Young Scientists Conference 'High-Performance Computing and Simulation' was organized by ITMO University and University of Amsterdam, Netherlands. This conference also became annual, and it was held in Amsterdam in 2012, in Barcelona in 2013 (in frames of International Conference on Computational Science 2013), in Amsterdam in 2014 (organized by ITMO University, University of Amsterdam and Skolkovo

Institute of Science and Technology, Russia), and in Athens in 2015 (organized by ITMO University, University of Amsterdam, National Technical University of Athens and Nanyang Technological University, Singapore).

Transdisciplinary group projects as a specific type of educational activity were primarily developed and implemented in a course of 2014 nationwide School (the details of implementation and a discussion of the results can be found in [27]). Traditional educational activities such as lectures, master classes and scientific presentations of participants were supplemented with two sessions devoted to group projects and one public session to present the results. Five groups of participants had to prepare suggestions on simulation of a big city by means of BigData and HPC with a focus on a question: "How can the functioning and evolution of a big city be described with a set of multi-scale computer models?". This problem satisfies all criteria described in Section 4, namely, it is ill-defined, complex, allows broad conception and lays at the intersection of several research areas. High resulting marks of group projects (the jury's marks varied from 21.16 to 25.5 from 32) proved that in the end participants have been able to cope with transdisciplinary problem. The analysis of participants' feedback showed that the average score of the collaborative activities was 7.44 of 10, 49% of the participants found these activities useful for their current work and/or investigations, and 97% would attend such training again. These results were convincing enough to include group projects to a program of schools on a regular basis.

The theme of 2015 nationwide School was 'A Study of Global Systems', and the goal of a transdisciplinary project was to develop the description of a model of the global system from any desired domain. This year we added to a program a new type of social activity called interactive acquaintance (see Fig. 2) which is performed on the first day of the event. This activity sets out understandings of participants about both scientific directions and personal characteristics of their colleagues and corresponds to a step C (formation of a community) in Fig. 3. As for group projects, we provide to participants a list of possible areas (Internet, Climate, City, Scientific Community, Human Body, Epidemiology, Transportation), and a list of directions which should be covered in their presentations (description of a modeling object and levels of modeling, simulation methods, a structure of a model, existing software solutions and software have to be developed). The results provided by teams and the feedback of participants were essentially those that had been obtained in 2014.

The two-week duration of 4th Young Scientists Conference 2015 [22] in Athens, Greece provided new opportunities and new challenges for the deployment of TLE. Based on the experience of maintenance of two nationwide schools, we developed formalized schemes and procedures of their implementation presented in Sections 3 and 4, and then design a schedule of an event according to main stages presented in Fig. 2. Table 1 illustrates a grid of main activities in the course of the School According to Fig. 2, we distinguish social, educational and team activities.

Each of days 4–6 of the event included two sessions of team work with the duration per day equal to 2.45 hours, and a single session was performed on day 7. So, the total duration of team work was significantly larger in comparison to the previous schools. According to this, we expanded the goal of team work as to design a competitive grant proposal including topicality, potential beneficiaries, modeling methods, description of a model, the state-of-the-art of the field, existing solutions,

Table 1. Schedule of YSC-2015 (—social activities; 2—educational activities, general; 3—educational activities, individual; 4—team activities)

DAY 1	Welcome address (1)	Lecture (2)	Interactive acquaintance (1)	Lecture (2)	Lecture (2)	Discussion (2)	Excursion (1)
DAY 2	Master class (2)	Presentations (3)	Presentations (3)	Lecture (2)	Discussion (2)	Group project announcement (4)	Welcome party (1)
DAY 3	Excursion (1)						
DAY 4	Lecture (2)	Presentations (3)	Lecture (2)	Presentations (3)	Master class (2)	Group projects (4)	
DAY 5	Group projects (4)	Lecture (2)	Presentations (3)	Lecture (2)	Presentations (3)	Master class (2)	Group projects (4)
DAY 6	Group projects (4)	Lecture (2)	Presentations (3)	Lecture (2)	Presentations (3)	Group projects (4)	
DAY 7	Group projects (4)	Lecture (2)	Team presentation (4)		Award ceremony (4)		

timeline of implementation and desired outcomes. To divide the participants into teams, we suggest them to fill the initial questionnaires on the first day of an event. We use responses to form teams of participants with different experiences and specializations and to choose preferable directions of their activity, namely, Climate, Big City, Epidemiology, Traffic, Web 2.0 and Virtual Reality. The choice of a particular research problem was given to participants. The analysis of responses showed that, in general, all participants can be divided into two groups: those who had several published papers and several years of research experience (experienced participants) and those who had approximately one year of research experience and no more than one paper (inexperienced participants).

We performed intermediate monitoring of team activity by gathering everyday reports on the progress of teams. The reports' analysis showed that the consequence of activities during team work corresponds to those in the knowledge transfer cycle (Fig. 3): during the first session team members achieved a deeper understanding of each other's skills and chose the general direction of research, then they performed a knowledge acquisition in a chosen field, and the latter was the creation of new knowledge. Themes of grant proposals presented during the public session varied from the intellectual prediction of criminal activities and solving the problem of urban heat islands to the modeling of small-scale spatial events. Group projects were evaluated on the last day of the event during public session judged by the panel of experts. According to jury marks, six teams have been distributed uniformly between three types: two teams were leaders, two belonged to the middle, and the remaining two teams were outsiders.

In addition, we compare the topicality of projects presented by participants with the areas of their proficiency which they indicated in the questionnaires. The detailed description of a method and the numerical results are presented in [30]. The main conclusions that could be drawn from the analysis are: (i) experienced participants tend not to change their major research area during team work while inexperienced participants are more flexible to changes; (ii) teams that chose a topic of the project with account of current specializations and skills of its members achieved best results. The first conclusion implies that inexperienced participants are sensitive to the influence of experienced participants, which, in turn, catalyze knowledge transfer process and act as teachers for less experienced colleagues.

Estimation of the level of which transdisciplinary competencies are improved in frames of short-term learning environment is non-trivial both because of their tacit nature and time restrictions of an event. Recognizing this, we aimed short-term TLE at getting a glimpse of working in multidisciplinary teams on complex real-world problems rather than a mastery of long-term transdisciplinary competencies in the participants. We would like to familiarize our students with the difficulties that members of transdisciplinary team face, and give them try their powers in changing usual patterns of educational and research activity. The results shown by groups and, possibly more important, participants' feedback give us hope that we as organizers reach these goals in the course of short-term educational events in the area of Computational Science. As an indicative verification of high quality of proposed projects we can mention the fact that students from 2016 nationwide School won recent IT-Breakthrough competition [31] with a project based on the results of their team work in the course of School. The main limitations of the study are: (i) proposed approach is mostly applicable to introduce the concept of transdisciplinarity to students rather than to master transdisciplinary competencies, (ii) proposed methodic is tailored for short-term events in Computational Science as ICT serve as a binding basis for group solving of ill-defined problems. However, the foundational principles of TLE creation remain the same for various duration of knowledge transfer cycle and areas of deployment.

The emergence and growing number of transdisciplinary problems is caused by growing diversification of areas of human knowledge. For the engineers of the future, it is not enough to become a professional within their narrow specialization. In addition to intensive development (i.e. improvement in the framework of their discipline), they must be able to treat the problem at the high level of abstraction, finding consensus with experts from other fields. This explains the importance of transdisciplinary education for today's engineering students, which in turn requires the development of new educational approaches for the mastery of transdisciplinary competencies and corresponding methods of evaluation. The methodic presented in the current study allows to give students an initial idea of what transdisciplinary problem is and how to work on it collaboratively. The next step in this direction could be the addition of transdisciplinary activities into the curriculum of medium- and long-term educational programs in order to foster the skills of collaborative solving of complex, ill-defined problems at the junction of several knowledge fields.

5. Conclusion

In this paper, we propose a methodic that enables to familiarize students with the concept of transdisciplinarity in the course of short-term educational activities via practice of group solving of nontrivial ill-defined tasks. We describe main principles of design and deployment of short-term transdisciplinary learning environments including the issues of purposeful scheduling of such events. To create a sustained basis for knowledge production during a short-term event, we organize the activities of participants in varying roles within two interconnected levels of a knowledge transfer cycle. Proposed methodic was evaluated in several nationwide and international young scientists' conferences in the area of Computational Science. Analysis of participants' feedback, jury's marks and topicalities of group projects in short-term TLEs allow draw the following conclusions: (i) groups of participants with different background are able to cope with transdisciplinary problem after being immersed into TLE, (ii) consequence of activities during team work corresponds to those in the proposed knowledge transfer cycle, (iii) previous research experience of participants influences their flexibility in the choice of an area during a short-term team work. Presented results being combined with methods of evaluating transdisciplinary competencies can serve as a basis for a mid- and long-term transdisciplinary education programs.

Acknowledgements—This paper is financially supported by The Russian Scientific Foundation, Agreement #14-21-00137-П of 02.05.2017.

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Klavdiya Bochenina is a researcher at eScience Research Institute at ITMO University (Saint-Petersburg). She obtained a PhD in computer science from the same institution with a work on scientific workflow scheduling. Her research activities are focused on several fields including distributed systems, algorithms design and transdisciplinary education.

Anna Bilyatdinova is a Lecturer at High Performance Computing Department and a Research Assistant at eScience Research Institute in ITMO University. Together with her colleagues from ITMO University and UvA, she participated in development and launch of the first in Russia Double Degree Master's program and annual international Young Scientist Conference in Computational Science. Her major research interests are Distributed Environments for Multidisciplinary Researches, Creative, Collaborative and Constructivist Learning, Internationalization of Russian Higher Education, Curricula and Syllabus Design. Her recent work is dedicated to development, organization and support of Learning Environments with the use of modern, developing and arising ICTs.

Alexey Dukhanov is an Associate Professor at the High-Performance Computing Department and a Senior Researcher at the eScience Research Institute at ITMO University. In 2011, he and his colleagues from ITMO University and UvA developed and launched the first in Russia Double Degree Master's program in Computer Science. His major research interests are Cloud Computing Technologies and Distributed Computing in Learning Resource Design and Implementation, Learning Courses and Resources Design Automatization, and ICT in Economics. He is a co-author of more than 30 papers in Russian and International Journals published in the last five years (2011–2016).

Gerassimos Athanassoulis is a Professor in School of Naval Architecture and Marine Engineering of National Technical University of Athens. His major research interests are free-surface hydrodynamics, hydromechanical systems, partial differential equations, stochastic modeling and analysis of environmental parameters, and wave phenomena in the sea. He published more than 50 papers in peer-reviewed journals and supervised 10 doctoral dissertations. He is a member of several scientific societies and international committees.