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Designing Contexts for Learning Design*

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Any learning activity including learning to design takes place in a particular context. Given the goals of the learning activity, this context could be designed, in a way that other products are designed, to satisfy its goals. In a reflective consistent discipline, such as design research could be, design researchers that develop design tools, use these tools to design their research. We present a case study in which a mechatronics design course for high school students was designed using design tools. The course design included teaching design tools. A controlled study showed that the design of the course led to outstanding results. Students engaged in the course, compared to students who studied fewer design tools, won an international robotics competition, improved their science grades, displayed superior design skills, and improved their technology perception. These results demonstrated that by careful design, successful contexts for learning design could be created. In addition, they demonstrated that being reflectively consistent in design research is rewarding. In summary, we also present ideas for further improving the design of the design course.

Keywords: design education; reflective consistency; mechatronics; robotics contest; controlled study; high-school.

INTRODUCTION

CONTEXT MATTERS! It matters whether it is the environment in which learning takes place or the prior knowledge and presuppositions with which learners interpret and comprehend new knowledge. Context consists of:

- the educational institute and its available resources;
- the teaching material and process;
- the knowledge of students and their cultural orientation;
- the community associated with the learning activity.

This context has significant influence on the process and outcome of learning [1, 2].

If context matters, then we should be designing it to improve learning. As design researchers, we develop theories, methods, and tools for supporting design activities. As design educators, we design courses and apply them in the practice of teaching. These research and practice activities create a rare situation in which our design theories (which are intended to be used by others, i.e., designers) could be used by us to assist us in our practical educational activities. A discipline that fosters the practice of its research products within itself and constantly reflects upon these activities to improve them is called a 'reflective consistent' discipline [3].

There is significant benefit to being reflectively consistent. First, by testing our own tools on our own problems we create quick feedback loops that could assist the further development of the tools and subsequently obtaining better designs (e.g. courses). Second, we do not release tools that are flawed.

Of all disciplines, Engineering Design must lead the way to being reflectively consistent. After all, it originates many tools, and as other disciplines, it needs these tools to overcome systemic complexities in the artifacts it creates and uses. Nevertheless, thus far, the challenge has hardly been met. This discrepancy is one driver of this paper. For more than a decade, we have been at the forefront of advocating for a better connection between design theory and practice [4, 5]. We were able to further demonstrate such connection when the first author participated in developing the collaborative design support system *n*-dim [6, 7]. As shown in Fig. 1, the *n*-dim project was driven by an infrastructure composed of a philosophy, development methods, software, and tools. These directed the development of applications that were embedded in particular contexts. Following these implementations, empirical studies determined the success of the project and with it, provided feedback to the infrastructure and application. Every aspect of this endeavor including this figure was malleable thus had to constantly sustain successful empirical study. This constant reflection was instrumental in the success of the numerous educational and industrial applications developed in this project [8].

A tight relation between theory and practice is observed also the present study but moreover, this study is reflectively consistent as it utilizes design methods to design educational setup. Furthermore, the educational setup is a design course thus utilizing again methods from the same pool hence stretching the concept of reflective consistency even further: not only do we trust the

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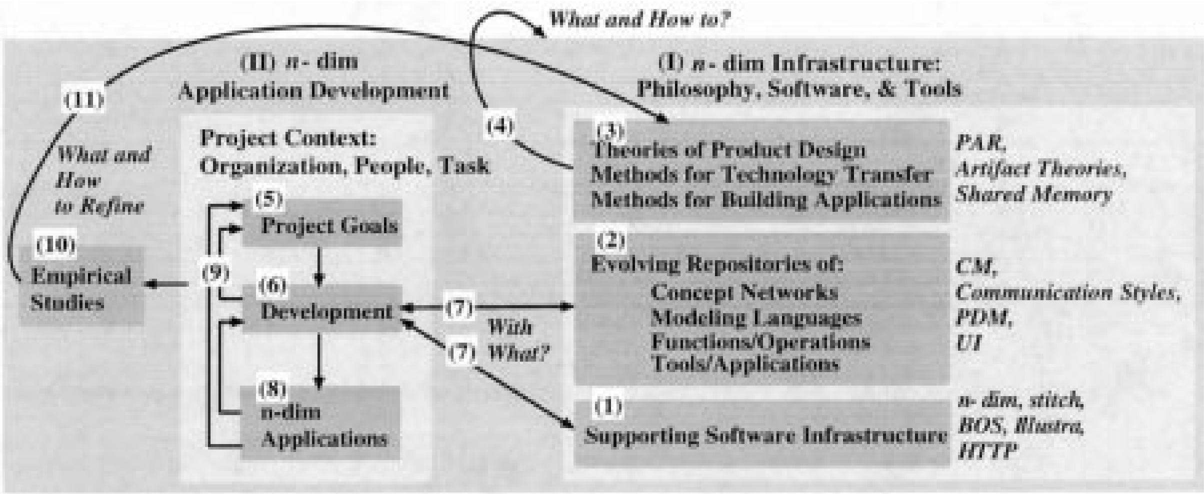

Fig. 1. The n-dim project cycle [6].

methods and use them in our practice; we also trust that they would be useful to our students and put all this trust into empirical testing. In this study, we show that being reflectively consistent in design leads to better design education. More specifically, our study shows that a careful design of a project-based design course (compared to inferior designs) leads to:

- improved design skills (compared to those acquired in inferior course designs) measured by product competition performance and traditional tests;
- improved learning of related courses measured by traditional tests;
- improved attitude toward technology measured by a survey.

Learning how students perform in a project-based course leads to better course design. This learning arises primarily from observing failure of students to apply their theoretical design knowledge.

By this demonstration, we provide an example that research and practice need not be separated. Moreover, to be taken seriously by users of our research, we design researchers should test our tools in our own reality whenever possible. These observations constitute the 'weak' form of our position. The 'strong form' contends that being reflectively consistent is the best approach to design. We demonstrate this for a product that is a context for learning design.

We start by describing an implicit quest for reflective consistency that has been encouraged by different researchers and continue with the practice of reflective consistency in designing a mechatronic design course. We describe the study, its results, and conclusions.

THE QUEST FOR REFLECTIVE CONSISTENCY IN DESIGN EDUCATION

It appears that the reflective consistency principle has been implicitly around for years. For example, it is embedded in the titles of two previous Mudd workshops: the 2nd 'Designing Engineering Design for the 21st Century' and the 4th 'Designing Engineering Education'. It has also been stated explicitly as conclusions from the 2nd Mudd workshop [9], e.g., design courses need to be designed (including the grading and assessment of student learning) and assessment and continuous improvement must be integrated into a course program. More recently, Dym [9] suggested that the answers to what to improve in engineering education and how 'could be greatly improved if some basic percepts from design theory and from systems analysis are brought into play as answers are sought (p. 308).' Dym continued by describing ingredients of the design process such as: eliciting objectives, articulating constraints, deriving functions whose execution realizes the objectives, and performing evaluation. The list of constraints he articulated is particularly interesting in demonstrating the different perspectives that participate in educational program design. Over years, systems thinkers and educators have also discussed the use of systems thinking in education, notably Banathy [11]. More recently, in addition to the traditional curriculum design literature, similar titles on systems thinking and design in education have appeared in the education literature (e.g. [12, 13]).

Finally, there are few studies that employed design methods for parts of the curriculum design task. Saunders and Saunders [14] used QFD (quality function deployment; [1]) to prioritize the engineering skills required of manufacturing engineers. This prioritization could be the first step in curriculum design according to external requirements. Kaminski *et al.* [16], used QFD to translate between course requirements and education activities. Last, Martin and Ishii [17] discussed the use of a structured process for designing a DFX (design for manufacturing) course. They considered students as customers, conducted surveys, proposed optional educational activities or topics, and evaluated them using Pugh concept selection.

Notwithstanding all this literature, we are unaware of a real experiment in which design tools have been used explicitly to design a design course and the design was tested and proved successful. We are not aware of a single such experiment, not to mention a long-term evolution of a course guided by system and design thinking and tools that has been evaluated in a controlled study involving several schools.

Being reflectively consistent in mechatronics course design

Our study started as a redesign activity of an existing course [18]. The 2nd author was engaged in developing and running a successful mechatronics course program in high schools throughout Israel.

The desire to improve the course arose mainly due to observing that the design of many robots was not robust thus led to frequent failures at the design contest. While the context has never been the main course goal and while the course was considered as successful [18], it was an opportunity to re-examine and improve it. By stating that we design the context of learning design we mean that we considered all course-related decisions including:

1. Course curriculum.
2. Teaching strategies.
3. Students prior perception of technology and knowledge.
4. School resources such as teachers and labs.

The present design dealt with changing the first three items while using the latter as constraints. Fig. 2 depicts the process we used to design the context of learning design. It consists of two main steps: the design of the course and its implementation.

The course design is subdivided into three steps:

1. *Requirements collection and analysis:* The requirements come from studying designers but also from anticipating the future needs in future design environments. Design techniques that could be used include: task analysis, idea generation techniques such as brainstorming, surveys, QFD, and FMEA.
2. *Goals setting:* The requirements or needs of future designers are translated into course goals and learning activities that could support them. Supporting design techniques for this step include: QFD, RQFD [19], and influence graphs [20].
3. *Means identification, selection, and generation:* The course goals are matched with specific design methods, learning exercises, and other means to address them. Supporting design techniques include: creativity methods, QFD, function-means trees [21] or graphs, AHP [22], design for variety [23], influence graphs [20], Pugh concept selection [24], and SOS [25]. In some cases, available methods are insufficient to address the needs properly. This may lead to suboptimal solution or to the initiation of a research project to develop suitable methods. This is important feedback that educational practice could provide to the engineering design community.

The first step in designing the mechatronics course involved a rationale reconstruction of the course design, starting with the course goals down to its ingredients [26]. The following goals were identified:

- acquiring technical knowledge;
- acquiring system thinking approach;
- improving skills of problem solving, decision making, and learning;
- developing critical and creative thinking abilities;
- experiencing development of a product, with time and budget restrictions;

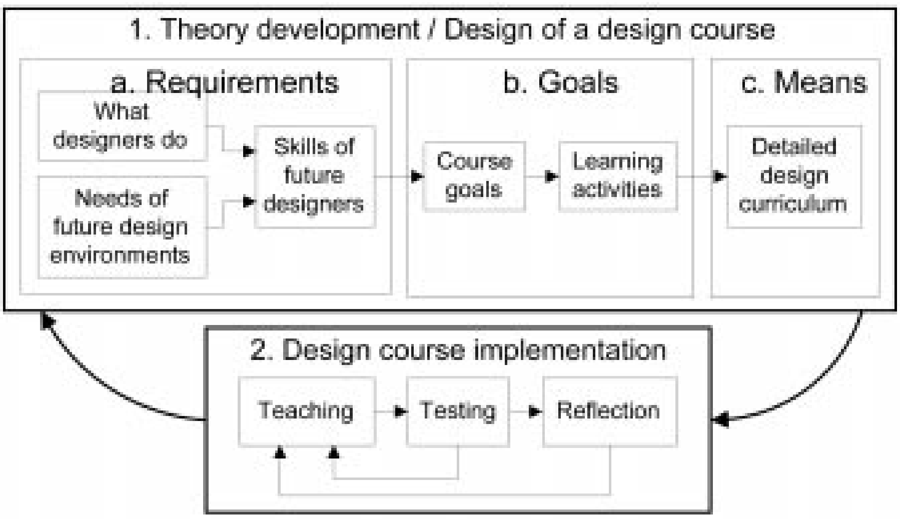

Fig. 2. Being reflectively consistent about designing context for learning design.

Table 1. Mechatronics course learning subjects

Learning subjects	Topics and relevant design methods
1 Mechanics	Materials, Statics and dynamics, Motors and gears (conceptual design, creativity, ATR– atomic requirements, FT—fault tolerant)
2 Electronics	Fundamental concepts and electronic circuits, Components and integrated circuits, Digital and analog electronics, control (conceptual design, creativity, ATR, FT)
3 Computers	Logic and Boolean algebra, Hardware, Serial communication, address, data and control buses (conceptual design, creativity, ATR, microprogramming)
4 Software	Microprocessor structure and addressing modes, Assembly language instructions and commands, interpreter, 'high language' application, Input/output, interrupts and communication implementation by software, Robot control (conceptual design, creativity, ATR, FT microprogramming)
5 Control	Control types, Motor control, Speed and distance PID control, Robot movement closed loop control (conceptual design, creativity, FT, FL, microprogramming)
6 Robotics	Robot design considerations, Integrating hardware and software, Sensor's types (conceptual design, creativity, ATR, FT)
7 Laboratory	Electronic PCB construction, Designing and building a robot, Final tests, troubleshooting, debugging and fixing (ATR, FT)
8 Creative projects	Practical mini project, Theoretical mini research (all methods)

- developing teamwork skills;
- improving students' perception of technology.

Function-means graphs were used to break down the course goals and match potential means. Failure analysis was conducted to identify curriculum material that is missing from the course. Failure-mode-and-effect analysis was used to detect potential failures of the revised course design and propose additional changes and AHP was used to assess the relative importance of different curriculum material. The final course design is shown in Table 1; a detailed description of the methods and their role in the course can be found in [27]. The topics are taught taking into account the knowledge of the students. Some topics such as fuzzy logic are simplified to allow their accommodation, while retaining their usefulness. To improve the motivation of students to the level required in such demanding course, various exercises including creative projects are conducted.

In the future, we intend to refine this design further by using two additional design tools. RQFD will be used to allocate the time resource into the different educational activities and curricular material and SOS will be used for configuring different learning contexts for different schools depending on available resources and their existing context. We consider also increasing the pool of methods available to students to include SOS.

The course implementation was and still is a continuous teaching, assessment, and reflection cycle. In order to test the course design, we designed a controlled study involving four high schools and 104 students (see Table 2). Schools were located within the center of Israel and are named A, B, C and D. Some of the teams (50 students) produced fire-fighting robots (ffr) and some (54 students) produced other mobile robot projects. Table 2 presents student numbers in each school with the relevant projects.

All the students had general scientific background and they participated in a mobile robot project. Students in the different schools learned different curriculum:

- students at school A were taught the complete suite of methods;
- students at school B were not taught ASIT and microprogramming design, while ATR was taught as a regular requirement documentation;
- students at school C were taught only conceptual design; and
- students at school D were taught no method.

Students that were not taught a particular subject were taught other material instead to balance the hours of frontal teaching. This setup allowed us to assess the impact of different course designs on the course goals.

Teaching methods included:

- frontal teaching;
- experimental laboratory;
- team and individual guidance;
- teamwork and peer learning;
- motivation exercises; and
- research based on professional literature and Internet information.

Table 2. Student participation in the experiment

School	Students participating in ffr	No of teams ffr teams	Students participating in other robot project	No of students in other robot projects
A	20	2	—	—
B	14	2	29	$2 \div 4$
C	6	1	25	$2 \div 4$
D	16	2	—	—

The most appropriate teaching method was used for each of the subject matters.

RESULTS

Assessment of design capability is not easy. In order to evaluate it and other learning outcomes we employed three levels of testing:

- First, at the objective general level, we tested the impact of the mechatronic curriculum on the scores of students in general science disciplines (mathematics, physics, and chemistry).
- Second, at the objective particular level, we tested particular design skills by students' success in a design contest, expert evaluations of the designs, design tests, peer evaluations, and attitude questionnaire.
- Third, at the subjective level, we interviewed the students and got their opinion on the process and on their design skills improvement as they see it.

The results of the three levels showed that the more design methods students learned the higher their scores were in the three tests. In particular, in the context of the first level, we conducted several statistical analyses to check the effect of the different curricula on the scores student achieved in the different science disciplines (mathematics, physics and chemistry). We eliminated the effect of the differences in the pre-course grades. The results of a paired samples t-test with significance of 5% (conservative), shows that for each science subject analyzed separately (again conservative), students that studied more design methods, improved their grades more than those who studied less design methods. This demonstrates that the design course teaches general skills that improve general academic performance and might extend to other subjects than those tested. The results suggest that design skills are general. Therefore, learning design could provide a mechanism for adapting to an environment that requires constant learning and adaptation.

Second, at the objective particular level, we tested particular design skills by students' success in a design contest, expert evaluations of the designs, design tests, peer evaluations, and attitude questionnaire. Presently we only have partial evaluation of the results. Nevertheless, they point to the same conclusions. For example, in the international fire fighting competition held on April 2004 at Trinity College, Hartford, CT, the team from school A won 1st prize, team B finished 6th, team C finished 14th, and team D finished 16th place. The second team from school A did not participate in the contest due to misunderstanding in the registration even though they traveled to the contest from Israel in order to participate. Nevertheless, their robot was tested under the contest conditions in the same arena and got a score that would have given it 2nd place in the contest. The other two ffr robots did not travel to the international contest due to lack of funding.

The expert evaluation was corresponding to these results. The success in the contest shows that the particular process indeed makes a difference in creating designers with an understanding of addressing real design situations with state-of-the-art design tools like microprogramming and fault tolerance methods [28] along with various conceptual and detailed design methods. Initial examination of the other data suggests the same direction but we have not yet analyzed the results.

Third, at the subjective level, we interviewed the students and got their opinion on the process and on their design skills improvement as they see it. It was clear that students who studied the full program had a better sense of control over the robot functioning. Its robustness and superior technology gave them a sense of pride.

It seems that the course had a good balance between the teaching of subject matters, design activities, and product construction. It enabled students to acquire the skills mentioned before. Altogether, our design—the context of learning design—succeeded in delivering the required results. Students improved their problem solving skills, improved their attitude toward technology and showed unsurpassed motivation. They demonstrated design skills and through extensive teamwork, improved their social skills. Students master systems view of mechatronics products and the related factual and method knowledge. They came to appreciate the importance of managing time and other resources for the successful and timely completion of the robot.

DISCUSSION AND CONCLUSIONS

Our design is clearly context dependent. Although we set as a goal to design the context of learning, there are baseline characteristics of an existing environment that cannot be changed or that were kept outside the scope of our design. For example, the physical resources available for teaching (e.g., laboratories) are not part of the design. If necessary, they could be incorporated as well. The solution in this case, would have to involve creative ways of generating the experience that labs provide without having them at school or the solution would involve fundraising to establish labs.

There are however differences between the educational contexts of different schools that do not relate to physical resources. For example, some schools do not have teachers knowledgeable in all needed disciplines or methods. The available resources change the teaching activities that could be planned and therefore, impact the course results. Therefore, for each such context, a different educational process and content might be suitable. In addition, different schools might place different priorities over some of the goals or even introduce new goals. This creates a complex problem that is difficult to solve. In the future, we intend to use a general concept and configuration generation method, SOS [25], together with a flexible resource allocation tool RQFD [19], to set up the appropriate course structure for each context in order to maximize the course objectives.

SOS would analyze the available resources and maximize the course objectives with the available resources. This will create a list of subjects and design methods to teach in class. Subsequently, RQFD would be used to assist allocating the time for each subject in order to maximize the course objectives.

The same approach would also allow for making changes to class material while the course is running. Such unforeseen changes could result from sudden budget cuts, difficulties running laboratories or new laboratories that become available, as well as teachers leaving or joining the school system. The ability of SOS and RQFD to assist in managing such situations could be advantageous. In such cases, design tools used in designing learning contexts support our strong reflective consistency principle: they provide a benefit that without them is almost impossible to realize.

While the focus of this paper has been on designing high school contexts for learning, we envision that similar results would be obtained if the same methods were applied to universities or industry. The same ideas could be applied also to designing contexts for research in addition to learning. Since they are all products, they could be the end result of a design activity.

We discussed the implementation of the course design and the results demonstrating its significant impact (e.g. improved academic performance, winning first and other good places in an international robot contest, and improved technology perception). Since design is context dependent, our study should be considered in its context, namely, designing learning contexts for mechatronics for high-school students who are expected to design, produce, and operate a mobile robot in robot competitions. Nevertheless, we contend that the same approach would work for other design disciplines and for universities as well as industry.

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