Systemic Design of Interactive Learning Environment for Global Engineering Courses*

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This study investigates the interplay among design method, technology enhanced learning, and global engineering learning. It presents the process of how a team of engineering educators employed a set of design methods to integrate a variety of learning technologies in order to develop an interactive learning environment, upon which, multiple global engineering courses have been successfully developed. The designers went through a systemic design process of stakeholder involvement, functional design, and conceptual design. As a result, two key functional requirements of the interactive learning environment are proposed: (1) connect globally distributed classrooms and (2) promote peer-to-peer interactions among global learners. And two corresponding design concepts are generated: (1) videoconferencing classroom and (2) interactive eLearning system. An evaluation was conducted upon a particular global engineering course, namely “Principles and Practices of Global Innovation”, which was served by 130 students who signed up from six global universities. At the conclusion of the course, an evaluation was conducted to solicit the participants’ satisfaction with the interactive learning environment, and the impacts of this unique technology-enabled global learning experience on their knowledge, skill and attitude of Information and Communication Technology.

Keywords: Keywords: design method; technology enhanced learning; global engineering learning

1. Introduction

Thomas Friedman once said that the world has become “flat” because of globalization and information technology [1], and the average is “officially gone” in a hyper-connected new world [2]. It can be argued that the world is not truly flat until higher education becomes flattened, and the world is not fully interconnected unless the globally distributed classrooms are connected. With such motivation, a technology-enhanced global program, namely iPodia, has been developed to promote the breakthrough paradigm of “classroom-without-borders” in engineering education [3]. Unlike the movement of Massive Open Online Course (MOOC) that strives to make knowledge content more accessible to global learners regardless their social statuses and locations, iPodia engages global learners in peer-peer interactions in order to deepen their contextual understandings of a subject matter. Thanks to the observant eyes of ethnographic researchers [4], the process of how a team of engineers relied on their disciplinary knowledge of “design thinking” to synthesize a variety of learning technologies in order to create an interactive learning environment for global engineering courses has been well documented and systemically made visible.

An interactive learning environment (ILE) is defined as a technical system made of multiple eLearning technologies, upon which, a global engineering course (GEC) can be offered right on its participants’ local campuses. A GEC is defined as a series of teaching and learning activities, focusing on a particular engineering subject of global importance, through which, globally distributed learners can engage in interactive and collaborative learning across physical, institutional, and cultural boundaries. On one hand, ILE and GEC are two tightly entangled notions. Both can be regarded as an instructional system, which is made of multiple interrelated components (e.g., learning technologies vs. learning activities), to realize a particular instructional process. On the other hand, the two notions must be explicitly differentiated. Strictly speaking, ILE is one of the many possible “means”, while not the only means, to achieve the “end” of GEC. For example, a GEC can be developed, with minimum eLearning technologies involved, by means of gathering a class of global students in one physical classroom/campus through the traditional oversea study or student exchange programs. An ILE, once finished, can accommodate a variety of different GECs that are taught by different instructors, enrolled in by diverse students, and addressing different engineering subjects.

To date, multiple global engineering courses (GECs) have been developed based on the interactive learning environment (ILE) proposed in this

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paper, and focusing on different subjects, for example, “global innovation”, “cyber security”, “global sustainability”, “affordable medical device”, etc. All these GECs were made possible by an independent, nonprofit, global engineering education consortium, the iPodia Alliance, the current members of which include: University of Southern California (USC) in USA; Peking University (PKU) and Tsinghua University (THU) in China; National Taiwan University (NTU) in Taiwan; Korea Advanced Institute of Science and Technology (KAIST) in South Korea; Technion—Israel Institute of Technology (TECHNION) in Israel; RWTH Aachen University (AACHEN) in Germany; India Institute of Technology (IIT) and Birla Institute of Technology and Science (BITS) in India; University of São Paulo (USP) in Brazil; and Qatar University (QU) in Qatar. A particular GEC, namely “Principles and Practices of Global Innovation”, was selected to accommodate a rigorous evaluation that is intended to validate the practical effectiveness of the proposed ILE. So far, this course has been offered for 6 years with a steady increase of participating universities, students, and instructors. In the 2015 spring semester, it was collaboratively offered by six universities (i.e., USC, PKU, THU, KAIST, BITS, and Technion) with the participation of 130 college students as well as 13 instructors and their teaching assistants.

The rest of this paper is organized as follows. Section 2 presents a literature review of past studies, based on which, three research questions are framed. Section 3 reflects the ILE design process that is specified through three design phases: stakeholder involvement, functional design, and conceptual design. Section 4 elaborates the final design outcome. Section 5 shows a rigorous evaluation of the proposed ILE based on an existing GLE. Section 6 presents some discussions of the evaluation results, new knowledge added, and limitations. Section 7 draws conclusions and outlines future work.

2. Research questions

Design is a creative activity that characterizes human intelligence in general and the engineering profession in particular. Based on observations of good design practices, various design methodologies are developed to guide a systemic design process towards a better design outcome. To date, many design methods have been developed and proven effective to support different design activities, phases and scenarios. Some representing examples include but are not limited to: Systemic Design [5], Quality Function Deployment [6], Axiomatic Design [7], TRIZ [8], etc. However, a great majority of these existing design methods were precisely tailored to the technical systems instead of social services such as an educational system. As a result, they were seldom used by engineers to design and/or redesign a technology-enhanced learning environment.

A technology-enhanced learning environment (TELE), by definition, means an instructional system, through which, students acquire knowledge or skill guided by instructors and facilitated by technologies. Wang and Hannafin highlighted the importance of design-based research on the development of TELEs, and proposed a set of basic principles of implementing design-based research with TELE [9]. Mor and Winters explicitly pointed out the critical role played by design in developing an interactive TELE [10], where the spotlight begins to target the “interactions” occurring in a TELE. Note that, their work was grounded based on Simon’s formulation of “design” as “the science of the artificial” [11], provides the theoretical foundation of many design methods. Thereafter, Winters and Mor further suggested that designing a TELE system is a highly interdisciplinary process, which should be explored from both pedagogical and technical dimensions [12]. Despite the obvious contributions of these previous studies, most of them were initialized by education researchers instead of engineering designers. As a result, they tend to over-emphasize on the pedagogical dimension in terms of, for example, how to employ design thinking to enhance the teaching process [13], to promote collaborative learning [14], etc. In contrast, few efforts have been devoted to exploring the technical dimension of how to leverage design thinking to guide the synthesis of those separate learning technologies towards a more functional, adaptive, and responsive system, which is the focus of this study.

The critical role played by a certain global learning experience in forming a “complete” engineer for the 21st century has been repeatedly highlighted by a number of past studies [15]. There were many prescriptions of how to educate an engineer to become a global citizen with the necessary global preparedness [16], global competence [17], and professional skills [18]. To date, students gain a global learning experience mostly through overseas study programs, student exchange programs [19], and increasingly the capstone design courses conducted partially or completely overseas [20–23], which all depend on international travels. As a result, until today, the global learning experience remains a privilege of a few elite students, as opposed to a basic “right” of the many if not all students [24]. It should be made explicit though, by no means are we arguing that a technology-enabled global learning experience is effective enough to completely replace international travel. But rather,
it should be treated as an alternative means or an addition to the existing approaches, which is more scalable and cost-effective to both universities and students.

This study aims to address three specific research questions through Sections 3–5. These questions each correspond to the purposefulness, functionality, and performance of the proposed ILE.

- **Q1**: How and in what ways certain design methods can be used to streamline the design decision making process of building an interactive learning environment?
- **Q2**: What kinds of learning technologies are needed to make possible a global engineering course, and how to synthesize them together towards an integrated system?
- **Q3**: What is the practical effectiveness (or actual preformation) of the interactive learning environment?
  - **Q31**: To what degree are the participating students satisfied with the ILE and GEC?
  - **Q32**: What are the impacts on participant’s knowledge, skill, and attitude of ICT?

3. Reflection of design process

3.1 Stakeholder involvement

The design process has been driven by two key stakeholders (or chief designers): the authors Lu and Liu. Specifically, Lu is the director of the iPodia Program who initialized the vision, mission and strategy of the “classrooms-without-borders” paradigm; Liu is manager of the iPodia Program who is responsible for executing the design decisions and managing daily operations of the program. The author Morrison is another important designer. As a local instructor at KAIST, Morrison is continuously consulted by Lu and Liu with respect to those important design decisions. In addition, the three designers are design researchers, who specialize in the areas of design cognition [25–27], design method [28–29], and design education [30–31]. Last but not least, the three designers are also instructors of the GEC to be evaluated: Lu was the lead instructor who delivered the weekly lectures; Liu was one of the co-instructors who guided the team design project; and Morrison was one of the co-instructors who led the cross-cultural exercise. The author of Dai is a PhD candidate in education at the University of California Santa Barbara, and she played the role of using an ethnographic approach to observe, document, and make visible the entire design decision making process [4]. Besides, Dai was a former student and teaching assistant of the course, inspired by the experience of which, she gradually became interested, motivated and dedicated in understanding engineering education from the ethnographic perspective, even though her undergraduate major was cinematic art. This can be seen as another vivid example of the profound impacts of a unique global learning experience on a student’s long-term career development.

A systemic design process begins with involving the relevant stakeholders and soliciting their voices and resources. Creating a new learning environment for a global class involves more stakeholders than renovating an existing classroom for a local class. In particular, every decision must circulate around a group of stakeholders, who are affiliated to different universities, until a collective consensus is reached on every aspect of the ILE and GEC in terms of, for example, student recruitment, equipment compatibility, classroom scheduling, course assignment, grading scheme, etc. That being said, the stakeholder involvement process can be regarded as a collaborative negotiation process, where diverse objectives, perspectives, preferences must be equally considered and properly balanced. Table 1 summarizes the relevant stakeholders involved in the design process.

<table>
<thead>
<tr>
<th>Category</th>
<th>Stakeholder Position</th>
<th>Involvement Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Administrative</td>
<td>University administrators (e.g., university</td>
<td>Sign MOU to join the iPodia Alliance</td>
</tr>
<tr>
<td>Stakeholders</td>
<td>president or provost)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Department administrators (e.g., school deans</td>
<td>Approve course, allocate budget, designate responsible faculty</td>
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<td></td>
<td>department chairs)</td>
<td></td>
</tr>
<tr>
<td>Deployment stakeholders</td>
<td>Engineer, technician, operator</td>
<td>Install equipment, monitor network connection, record lectures, troubleshoot technical issues, etc.</td>
</tr>
<tr>
<td></td>
<td>Staff</td>
<td>Set up the course, advertise the course, register students, advise students, submit grade, etc.</td>
</tr>
<tr>
<td>Instructional</td>
<td>Instructor</td>
<td>Teach class, lead assignment, discipline students, determine grade, submit grade, etc.</td>
</tr>
<tr>
<td>stakeholders</td>
<td>Teaching assistant</td>
<td>Assistant the instructor to manage, teach the course</td>
</tr>
<tr>
<td>Research</td>
<td>Education researcher</td>
<td>Observe, document, evaluate learning process and outcome</td>
</tr>
<tr>
<td>stakeholders</td>
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ILE and GEC design. Table 2 summarizes the top five objectives (i.e., customer needs) of three key categories of stakeholders: university administrators, students, and instructors, as well as the methods through which these customer needs are collected.

The importance of engaging lead users in the design process has long been recognized by the design community [32]. Generally speaking, customer involvement for the purpose of design can be classified into three types: design for customer (i.e., customers are involved to define problems), design with customer (i.e., customers are involved to evaluate solutions), and design by customer (customers are involved to create new solutions). The two designers had adopted a customer involvement strategy, which is a hybrid of all three. First, at the conclusion of every class, the participating students are encouraged to thoroughly reflect their learning experience and report any problems that they had encountered by means of, for example, anonymous surveys, emails, focus group interviews, etc. Next, the students who raised questions are encouraged to actively contribute to the evaluation of any new solution before and after it is implemented. Last but not least, some lead users (i.e., those top-performing students who demonstrated an extraordinary level of motivation and responsibility) from precedent classes are identified, promoted to be teaching assistant (TA) of future classes and, upon the post, they are given the opportunity to directly propose new solutions.

### 3.2 Functional design

After relevant stakeholders are involved and the customer voices are solicited, the next phase is functional design, during which, a specific design problem is formulated as a set of functional requirements (FRs). The two chief designers followed the design method of Quality Function Deployment (QFD) to guide the functional design. QFD is a structured design method that translates qualitative design decisions (e.g., customer needs) into quantitative ones (i.e., functional requirements) for the sake of achieving higher quality. Traditionally, QFD has been widely used to redesign complex technical systems. Although there were a few applications of QFD to redesign services [33], to our best knowledge, there was no previous attempt of employing the method to design/redesign an instructional system, such as an ILE or a GEC. In the context of engineering education, QFD is adapted to translate the input of students’ voices to the output of instructor’s actions via a five-step process, as illustrated by Fig. 1.

Another important task in functional design is to differentiate functional requirements from design constraints. A good design is always driven by objectives (i.e., functional requirements), in the meantime, limited by boundaries (i.e., design constraints). Axiomatic Design Theory classifies various design constraints into two types: input constraint and system constraint. Furthermore, Liu and Lu had developed a constraint management method for conceptual design, which classified various design constraints into four more specific categories: internal input constraint, external input constraint, internal system constraint, and external system constraints [34]. In the ILE design process, the input constraints include, for example, Internet bandwidth, budget, time difference, academic calendar, grading policy, etc. And the system constraints include, for instance, student’s language proficiency, equipment capability, operator’s knowledge, etc.

After arriving at a set of functional requirements based on QFD, the designers followed the principles of “complete” (i.e., there is no design loss), “mini-

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<table>
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<tr>
<th>Stakeholders</th>
<th>Customer Needs</th>
<th>Channels</th>
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| School administrators | 1. Enhance the university’s global presence  
                         2. Make global learning experience more accessible to students  
                         3. Explore new alternatives of globalization strategy  
                         4. Complement the existing curriculum  
                         5. Promote innovations in engineering education | • In-person meeting  
                                                                              • Text analysis of email communications  
                                                                              • Conference or workshop |
| Students             | 1. Gain a better understanding of global innovation  
                         2. Interact with counterparts from other countries and cultures  
                         3. Establish and expand a global social network  
                         4. Experience a different kind of learning model  
                         5. Learn from best teachers in other universities | • In-person interview  
                                                                              • Office hour meetings  
                                                                              • Course evaluation  
                                                                              • Text analysis of email communications |
| Instructor           | 1. Participate in a transformative education experiment  
                         2. Sharpen teaching skill in front of international students  
                         3. Fulfill teaching obligation  
                         4. Receive a good course evaluation  
                         5. Implement new pedagogy | • In-person interview  
                                                                              • Focus group interview  
                                                                              • Text analysis of email communications |
mal” (i.e., there is no design redundancy), and “independent” (i.e., there is no unnecessary coupling), which are all prescribed by the Axiomatic Design Theory [7], to organize all FRs into a functional hierarchy, as illustrated in Fig. 2.

### 3.3 Conceptual design

Conceptual design is the design phase when the intangible functional requirements (FRs) are mapped to tangible design parameters (DPs) under various design constraints. Conceptual design consists of concept generation and concept selection. The two chief designers had followed the method of Analysis-Synthesis-Alternation to generate multiple concepts, and the two axioms prescribed by Axiomatic Design to select the best concept, respectively. The final result of conceptual design is illustrated by Fig. 3.

Analysis Synthesis Alternation (ASA) is a concept generation method developed by Liu and Lu, based on their long-term studies of innovative design thinking [28]. It adopts the formal definitions of analytic and synthetic propositions in logic to generate design concepts via systemic alternations between analysis and synthesis, back-and-forth coevolution between problem and solution domains, and progressive zigzagging across adjacent abstraction layers. Since ASA formulates concept generation as a proposition making activity, it allows the designers to: (1) collect and document important dialogues with the involved stakeholders that were made through emails, teleconference, and in person-meetings; (2) identify and abstract relevant design propositions out of the collected dialogues/discussions; (3) code these propositions as either analytic or synthetic propositions; (4) organize the coded analytic and synthetic propositions into functional and physical hierarchies.

![Fig. 1. Illustration of how to use QFD to guide functional design of the ILE.](image1)

![Fig. 2. Functional hierarchy of the interactive learning environment.](image2)
Axiomatic Design gained its name and reputation largely because of the two famous design axioms. The Independence Axiom suggests that the FRs and DPs should be related in a way that a certain DP is adjusted only to satisfy its corresponding FR without affecting other FRs. According to the Independence Axiom, there are three types of design concepts: uncoupled, decoupled and coupled concepts. As much as possible, the designers should select the uncoupled/decoupled concepts and eliminate the coupled ones. Among all the uncoupled concepts, the Information Axiom guides the designers to select the concept that has the least information content (or the maximum probability of success) as the final design solution. In practice, the two design axioms were strictly followed to compare and select the generated concepts. For example, there are three functional requirements, FR_132 (share lecture content in class), FR_211 (support academic interactions in class), and FR_221 (support collaborative interactions after class), which all can be satisfied by the same DP (web-conferencing platform). Without the Independence Axiom in mind, a natural decision would be to use one single web-conferencing platform to satisfy all three FRs at the same time, therefore leading to a coupled design. Guided by the Independence Axiom, the course was equipped with three separate web-conferencing platforms (i.e., WebEx, BlueJeans, and Skype). In class, instructor uses a classroom computer to share lecture content through WebEx, while students use their personal laptop/tablet/smartphone to interact through BlueJeans. After class, the global teams use Skype to collaborate on their innovation projects. By doing so, the three FRs are satisfied completely independent of each other. As a result, the final design solution manages to notably reduce the echoes in class, which can be caused by the reflection of audios between the classroom computer and students’ laptops.

Last but not least, conceptual design is the very design phase when various design constraints must be considered to filter those infeasible concepts. For example, limited by the input constraint of “budget”, the videoconferencing technology was chosen over the telepresence technology, even though the latter provides a more immersive experience; the shared Internet access was chosen over the dedicated Internet access, even though the former option often causes unexpected disconnections. Furthermore, limited by the system constraint of “shared Internet access”, the HD function of the videoconferencing codec was disabled; constrained by the capability of the videoconferencing codec (i.e., only one video stream, either students’ image or instructor’s image, can be transmitted at one time), an additional DP of “camera operator” was added to manually switch between the two streams.

4. Illustration of design outcome

This section presents the ILE design outcome, which is organized according to the two major FRs, the FR_1 (connect globally distributed classrooms) and FR_2 (promote peer-peer interactions among global learners), and their corresponding DPs, the DP_1 (videoconferencing classroom) and DP_2 (peer-peer interaction system).

4.1 Connect globally distributed classrooms

Videoconferencing technology is used to connect...
the globally distributed classrooms (FR1), making
each classroom a videoconference classroom. The
notion of “videoconferencing classroom” refers to a
multimedia classroom that is equipped with an
additional videoconferencing capability. Strictly
speaking, using videoconferencing technology to
connect those geographically distributed class-
rooms is not a completely new proposition, and
there were many previous studies that discussed
both advantages (e.g., reduction of cost and
increase of productivity) and disadvantages (i.e.,
students’ lack of sense of cohortness, instructor’s
lack of ability to manage the remote class) of this
approach [35, 36]. In the conceptual design phase,
three alternatives of DP1 were proposed and com-
pared: web-conferencing, videoconferencing, and
telepresence. Traditionally, web-conferencing is
often used to support the one-to-many communica-
tions, where the same content is delivered from one
central classroom to a large number of individual
users. As a result, it is found especially useful for
supporting distance education and web-seminars
[37, 38]. In recent years, there emerged growing
attempts of using web-conferencing technology to
connect the distributed classrooms [39, 40].
Although the fundamental difference between
web-conferencing (i.e., which is largely a software
solution) and videoconferencing (i.e., which
depends heavily on additional hardware such as
 codecs and high-definition cameras) is becoming
increasingly blurry, the latter still provides a
higher performance when it comes to the criteria
of two-way communication, face-to-face interac-
tion, and video-audio quality. It is for this reason
videoconferencing was selected over web-confer-
encing. On the other hand, telepresence is a further
advancement of videoconferencing. Telepresence is
a highly integrated system of various videoconfer-
encing technologies, which allows the distributed
users to feel as if they were meeting in the same
location. Compared to videoconferencing, on one
hand, telepresence features a more immersive
experience; on the other hand, however, it is also
associated with a much higher cost of installation
and maintenance with respect to, for example,
lighting system, air conditioning, furniture, and
dedicated Internet access. After the tradeoff
between performance and cost, videoconferencing
was chosen over telepresence. Unlike a telepresence
room that must be built from scratch, a videoconfer-
encing classroom can be built either by upgrading
a distance education classroom by adding the nec-
asary videoconferencing codecs, or through renovat-
ing a video conference room by adjusting the room
layout towards the classroom layout. Furthermore,
videoconferencing can run on either dedicated or
shared Internet access. Since the former violates the
input constraint of budget, the shared Internet
access (DP142) was selected. Finally, a multipoint
control unit (DP143) is used to bridge the connection
of more than 3 classrooms.

Microphone (DP11) functions to pick up sounds
(FR11) in a local classroom, and convert sounds into
electrical signals that can be recognized and trans-
mitted to a remote classroom through the video-
conferencing codec (DP141). FR11 is decomposed
into two sub-FRs: FR111 (pick up instructor’s sound)
and FR112 (pick up students’ sound). According to the Independence Axiom, two separate
microphones (i.e., sub-DPs) must be equipped.
Specifically, the instructor is equipped with a wire-
less tie-clip microphone (DP111). In terms of FR112,
three alternatives of DP112 were considered: (1)
handheld microphone, (2) ceiling microphone, and
(3) table microphone. Generally speaking, the three
alternatives all can satisfying FR112, and each alter-
native has its own advantages and disadvantages.
For example, the handheld microphone consumes
too much time to be passed around different stu-
dents, table microphones and ceiling microphones
automatically picks up too many background
noises (e.g., students typing keyboard, eating
food, or taking notes).

Camera is another important component in a
videoconferencing classroom, and it functions to
capture images and produce live video streams
(FR12) that can be transmitted through the video-
conferencing codec (DP141). The FR12 (capture
image) is decomposed into three sub-FRs: FR121
capture instructor’s image) and FR122 (capture
image of the speaking student), and FR123 (switch
between instructor’s and students’ image). Accord-
ing to the Independence Axiom, therefore, three
dPs were proposed: DP121 (rear camera), DP122
(audience camera), and DP123 (camera operator).
Most of mainstream videoconferencing codecs only
allow one video stream (either image of instructor or
students) to be transmitted at a time, hence, an
additional DP123 (camera operator) is added to
manually switch in between the two video streams.
His/her duty is to identify the active speaker(s),
switch between the rear and audience cameras,
and adjust the camera to catch the speaker accord-
ingly. In terms of a possible alternative of DP123, for
example, the classroom at KAIST is equipped with
a dynamic speaker tracking system in place of
camera operator, which automatically zooms to the
active speaker.

In terms of FR13 (to display), three alternatives of
DP13 (a display system) were considered: video wall,
projector screen, and HDTV screen. Video wall
provides the most immersive display experience,
however, its installation and maintenance cost is
also the highest. HDTV screens have a higher
resolution and brightness, however, the mainstream HDTV screens (e.g., 60"–80" inches) are not large enough to create an immersive user experience, in particular for a large class. As a result, most of iPodia classrooms are equipped with projector screens. FR1,3 can be decomposed into two sub-FRs: FR1,31 (display remote classrooms) and FR1,32 (display lecture content). Two screens are placed in the front of the classrooms: a projector screen to display the remote classrooms, and a HDTV screen to display the lecture content. Two HDTV screens are placed in the back of the classroom: one displays the remote classroom(s) and the other displays the lecture content. The front and rear screens are each prepared for the local students and instructor, respectively.

4.2 Support peer-to-peer interactions
Various student-student (peer-peer) interactions can be categorized into three kinds: academic, collaborative, and social interactions [41]. Based on such a classification, FR2 (promote peer-peer interactions) is decomposed into three sub-FRs: FR2,1 (support academic interactions), FR2,2 (support collaborative interactions), and FR2,3 (support social interactions). Furthermore, the designers also considered the dimension of synchronous vs. asynchronous interactions. As a result, FR2,1, FR2,2, and FR2,3 was each decomposed into two specific sub-FRs: FR2,1,1 (support synchronous academic interactions in class), FR2,1,2 (support asynchronous academic interactions after class), FR2,2,1 (support synchronous collaborative interactions in class), FR2,2,2 (support asynchronous collaborative interactions after class), FR2,3,1 (support synchronous social interactions after class), and FR2,3,2 (support asynchronous social interactions after class).

Academic peer-peer interactions occur both in class and after class. Web-conferencing platform (DP2,11) is proposed as a means to support the synchronous academic interactions in class (FR2,1,1). Specifically, all students are required to bring their personal laptop/tablet/smartphone to the local classroom, using which, to login the designated web-conferencing platform and interact with each other in the study groups formed by the instructor. The alternative web-conferencing platforms that were compared by the two designers include: Skype, Adobe Connect, WebEx, BlueJeans, Google Hangout, GoToMeeting, etc. Finally, the BlueJeans Platform was selected to be the final solution of DP2,11. On the other hand, online forum service (DP2,1,2) is proposed to support asynchronous academic interactions after class (FR2,1,2). Among various readily available forum services, Piazza was selected as the final solution of DP2,1,2, in light of former students’ recommendations [42].

Collaborative peer-peer interactions occur, when the globally distributed teams engage in virtual collaborations to jointly accomplish a team project. On one hand, the global teams need to hold virtual meetings to make synchronous collaborative interactions (FR2,2,1), which can be enabled by another web-conferencing platform (DP2,2,1). Specific choice of the web-conferencing platform was left for each team to decide, and most of teams had selected either Skype or Google Hangout. On the other hand, the global teams also need to maintain asynchronous collaborative interactions (FR2,2,2), which can be further decomposed into: FR2,2,2,1 (coordinate and schedule meetings) and FR2,2,2,2 (share and edit documents). In practice, in addition to the DP2,2,2 of “email” which is prescribed by the instructor, the global teams also used mobile messenger (DP2,3,1) and social networking service (DP2,3,2) to coordinate and schedule team meetings (FR2,2,2,1); and they used a variety of file hosting services (DP2,2,2,2), for example Google Docs or Dropbox, to share and edit documents (FR2,2,2,2).

It has been indicated by many past studies that social interaction plays an important role of enhancing teamwork effectiveness and increasing task productivity [43, 44]. This is especially true for the globally distributed teams, which must deal with a higher level of difficulty to overcome social barriers [45-46]. Therefore, the designers proposed to use mobile messenger (DP2,3,1) and social networking service (DP2,3,2) to support the synchronous social interactions (FR2,3,1) and asynchronous social interactions (FR2,3,2), respectively. Mobile messenger is a free communication-by-message service that is often installed on mobile devices. Common functions of a mainstream mobile messenger include: send/receive text messages, send/receive voice messages, send/receive videos, share locations, etc. Among many alternatives (e.g., WhatsApp, KakaoTalk, Facebook Messenger, etc.), the WeChat Messenger is selected as the final solution of DP2,3,1. With respect to the asynchronous social interactions, social networking service allows its users to expand their social network with those who share similar interest, background, and connections. According to the students, “expanding the global social network” is one of the most important motivators for them to sign up a global engineering course [47]. Note that, the “networking” needs can be further decomposed into social networking and professional networking, which can be each satisfied by Facebook and LinkedIn, respectively. The unique values of social capital for engineering students in an interactive learning environment have been indicated by Brown et al [48].
5. Evaluation methodology

5.1 Course overview

Based on the above described interactive learning environment (ILE), multiple global engineering courses (GLEs) have been successfully developed and offered. The particular course that the designers chose to evaluate is the flagship course of the iPodia program, namely “Principles and Practices of Global Innovation”. To date, the course has been consecutively offered for 6 years since 2009. The data for this study was collected from the 2015 spring class. Despite the calendar difference, all participating students learnt together for a total of 10 weeks, with a two hour lecture scheduled each week. As the course name suggests, it focuses on both engineering principles and practices. On one hand, a set of innovation-related concepts, principles and methods were systemically taught to the students via lectures. On the other hand, the class was divided into different forms of cohorts (i.e., study group, cross-cultural team, and project teams), which were tasked to practice what they learnt in class to collaboratively accomplish different assignments after class.

In terms of pedagogy, firstly, flipped classroom was adopted to promote peer-to-peer interactions [49]. The positive impacts of flipped classroom on students’ learning have been indicated by some previous studies [50]. Before the live class begins, students were tasked to first preview lecture materials by themselves, next provide individual feedback via a pain index survey (i.e., how painful they perceive each concept), and finally to engage in peer-to-peer interactions within a small cohort of 4~5 students (i.e., to teach each other the concepts they know better). By doing so, the instructor can make full use of the live class to interact with the students in specific to certain concepts that remain “painful” even after the peer-to-peer interactions. Secondly, project-based learning was also deployed. Specifically, the class was divided into 20 global teams, and they were tasked to collaboratively accomplish a design-oriented project of their own choice. The general project theme was to identify a sustainability issue on campus (e.g., paper waste, water waste, energy conservation, etc.), frame it as an engineering design problem, and propose initial design solutions. A final presentation was organized for all teams to present their innovation process and outcome in front of a panel of invited judges. The final deliverable was a five minute mini-movie. Finally, three cross-cultural exercises were organized to increase students’ understanding and improve their appreciation of others’ cultures. The exercise topics were: (1) produce a mini-movie to describe a campus culture; (2) make a presentation to picture a typical person in each culture; and (3) conduct a case study of a successful/unsuccessfully business that succeeds or fails for cultural reasons.

5.2 Course participants

The course enrolled a total of 130 college students, who signed up from six member universities of the iPodia Alliance: University of Southern California (USC), Peking University (PKU), Tsinghua University (THU), Korean Advanced Institute of Science and Technology (KAIST), Birla Institute of Technology and Science (BITS), and Technion—Israel Institute of Technology. The class was divided into two parallel sessions: Session A (i.e., USC+Technion+BITS) and Session B (i.e., USC+PKU+THU+KAIST). The Session A included 20 USC-A, 20 Technion, and 20 BITS students, and the Session B included 20 USC-B, 20 PKU, 10 THU, and 20 KAIST students. No limitation of students’ disciplines was imposed. As a result, for example, the USC class was composed of half engineering and half business students.

The course was developed and taught by a global teaching team, which consists of instructors (and their selected TAs and support staff) coming from the six participating universities. The course instructors are all affiliated to the engineering college/school/faculty, although they specialize in different engineering disciplines. Each instructor is assigned a relatively independent instructional role to design, organize, and lead a separate learning activity or course assignment. Such a separation of duties can be seen as another application of the Independence Axiom. In addition, every instructor is also responsible for managing the local class on their home campus in terms of, for example, classroom scheduling, student registration, class attendance, homework submission, course promotion and grade submission, etc.

5.3 Anonymous survey

At conclusion of the course, all participating students were asked, on a voluntary basis, to complete an anonymous survey, which was designed to solicit their satisfactions with different aspects of the ILE and GEC. It was made explicit to all students, in advance, that the survey result would not affect their final grades. A total of 118 responses were received, with a completion rate of 90.8%. Such a high completion rate implies that the students were effectively motivated and the survey was well executed. In terms of survey participants’ disciplinary background: 68% of them are engineering students, 14% of them are business students, 11% of them were science students, and 7% of them were humanity/art students.
5.4 Survey results

Figure 4 illustrates the students’ stratification with the videoconferencing classroom (DP1), and Fig. 5 illustrates the students’ satisfaction with the interactive eLearning system (DP2). The satisfaction was rated based on the scale of 1–5 (i.e. 1, 2, 3, 4 and 5 each represents “very unsatisfied”, “unsatisfied”, “neutral”, “satisfied”, and “very satisfied”). The videoconferencing classrooms located on different campuses are not designed exactly the same (e.g., some classrooms are equipped with ceiling microphones and projector screens, while some others are equipped with handheld microphones and LCD screens). Therefore, instead of diving into very specific sub-DPs, the students were only surveyed their general impressions on the audio and video system.

Figure 6 illustrates the students’ satisfaction with different aspects of the course in terms of “their overall satisfaction with the course”, “to what degree their learning objectives were realized”, “their satisfaction with the interactive learning experience”, “their satisfaction with the international learning experience”, “to what degree the course had deepened their understandings of global innovation”, and “to what degree the course had deepened their understandings of design thinking”.

Table 3 summarizes the impacts on students’ knowledge, skill and attitude of Information and Communication Technology (ICT). All participat-
Table 3. The opinions of students about the impacts on their knowledge, skill, and attitude of ICT

<table>
<thead>
<tr>
<th>ICT</th>
<th>Purpose</th>
<th>Specific surveyed question</th>
<th>Rating Result</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Knowledge</td>
<td>Access and evaluate information and communication technology</td>
<td>The iPodia experience improves my understanding of the main computer applications, including word processing, spreadsheets, databases, information storage and management</td>
<td>3.32</td>
<td>1.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The iPodia experience improves my awareness of the opportunities given by the use of Internet and communication via electronic media (e-mail, videoconferencing, other network tools) and the difference</td>
<td>3.99</td>
<td>0.72</td>
</tr>
<tr>
<td>Analyze media</td>
<td></td>
<td>The iPodia experience makes me understand both how and why media messages are constructed, and for what purposes</td>
<td>3.76</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The iPodia experience makes me examine how individuals interpret messages differently, how values and points of view are included or excluded, and how media can influence beliefs and behaviors</td>
<td>4.01</td>
<td>0.55</td>
</tr>
<tr>
<td>Create media product</td>
<td></td>
<td>The iPodia experience makes me understand the ethical/legal issues surrounding the access and use of media</td>
<td>3.59</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The iPodia experience makes me understand how to utilize the most appropriate media creation tools, characteristics, and conventions</td>
<td>3.92</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The iPodia experience makes me understand and know how to effectively utilize the most appropriate expressions and interpretations in diverse, multicultural environments</td>
<td>4.01</td>
<td>0.55</td>
</tr>
<tr>
<td>Skill</td>
<td>Access and evaluate ICT</td>
<td>The iPodia experience improves my skills to access ICT efficiently (time) and effectively (sources)</td>
<td>3.81</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The iPodia experience improves my skills to evaluate information and ICT tools critically and competently</td>
<td>3.85</td>
<td>0.58</td>
</tr>
<tr>
<td>Use and manage information</td>
<td></td>
<td>The iPodia experience improves my skills to use ICT accurately and creatively for the issue or problem at hand</td>
<td>3.86</td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The iPodia experience improves my skills to manage the flow of information from a wide variety of sources</td>
<td>3.87</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The iPodia experience makes me apply a fundamental understanding of the ethical/legal issues surrounding the access and use of ICT and media</td>
<td>3.68</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The iPodia experience makes my skills to employ knowledge and skills in the application of ICT and media to communicate, interrogate, present, and model</td>
<td>3.86</td>
<td>0.69</td>
</tr>
<tr>
<td>Create media products</td>
<td></td>
<td>The iPodia experience improves my skills to utilize the most appropriate media creation tools, characteristics and conventions, expressions, and interpretations in diverse, multicultural environments</td>
<td>3.93</td>
<td>0.63</td>
</tr>
<tr>
<td>Apply technology effectively</td>
<td></td>
<td>The iPodia experience improves my skills to use technology as a tool to research, organize, evaluate, and communicate information</td>
<td>3.87</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Use digital technologies (computers, PDAs, media players, GPS, etc.), communication/networking tools, and social networks appropriately to access, manage, integrate, evaluate, and create information to successfully function in a knowledge economy</td>
<td>4.07</td>
<td>0.67</td>
</tr>
<tr>
<td>Attitude, values, or ethics</td>
<td>Access and evaluate ITC</td>
<td>The iPodia experience makes me more open to new ideas, information, tools, and ways of working but evaluate information critically and competently</td>
<td>4.19</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>Use and manage information</td>
<td>The iPodia experience makes me use information more accurately and creatively for the issue or problem at hand respecting confidentiality, privacy, and intellectual rights</td>
<td>3.94</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The iPodia experience makes me manage the flow of information from a wide variety of sources with sensitivity and openness to cultural and social differences</td>
<td>4.11</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>Apply and employ technology with honesty and integrity</td>
<td>The iPodia experience makes me examine how individuals interpret messages differently, how values and points of view are included or excluded, and how media can influence beliefs and behaviors</td>
<td>4.11</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The iPodia experience makes me use technology as a tool to research, organize, evaluate, and communicate information more accurately and honestly with respect for sources and audience</td>
<td>4.04</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The iPodia experience makes me apply a fundamental understanding of the ethical/legal issues surrounding the access and use of information technologies</td>
<td>3.71</td>
<td>1.09</td>
</tr>
</tbody>
</table>
ing students were asked to indicate their level of agreement (i.e., “fully disagree”, “disagree”, “neutral”, “agree”, and “fully agree”) to a set of ICT-related survey questions. The results were converted into the numerical scores, according to the scale of 1–5 (i.e., the option of “fully disagree”, “disagree”, “neutral”, “agree”, and “fully agree”) each assigned the rating of 1, 2, 3, 4 and 5, respectively). The set of survey questions was directly adopted from a previous study [51], in which, ICT is recognized to be one of the key skills every college student must have in the 21st century. This set of questions was chosen for three reasons. Firstly, it holistically covers both social and technical dimensions of possible impacts of ICT. Secondly, the questions were phrased using relatively plain language that can be easily comprehended by students with different levels of English proficiency. Thirdly, the same set of questions has been used in multiple previous studies. Therefore, it leads to a future possibility of cross-examining other’s datasets with ours.

6. Discussions

6.1 Discussion of evaluation result

Although the satisfaction with the videoconferencing classroom is reasonably high (i.e., average = 4.175), it was suggested by some students that the current experience was far from immersive and spontaneous enough, compared to the face-to-face interactions. Based on the designers’ observations and diagnosis, this is largely due to the following reasons: (1) the high-definition video streaming is limited by the shared Internet access; (2) the four quadrant layout (i.e., each school occupies one quadrant of the screen) makes each school’s image very small on the projector screen; (3) it is ineffective to purely rely on the camera operator to identify and zoom-in the active speaker, and switches between the instructor and audience cameras were not always smooth; (4) when a local student speaks, he/she is inclined to stare at the display screen instead of the audience camera, causing a side-face view in sight of the remote students; (5) the instructor tends to pay much more attentions on the local students, while ignoring the remote students in terms of their learning “signals” such as raising questions, expressing confusion, being distracted; (6) there is no effective way to automatically balance the audio volumes of different classrooms towards the same level of volume; (7) the videoconferencing codec lacks the capability of sending two video streams (i.e., both instructor’s and students’ images) simultaneously; (8) the class was sometimes interrupted by occasional disconnections due to the shared Internet access.

The students’ satisfaction with the interactive eLearning system (i.e., average = 4.377) is slightly higher than that with the videoconferencing classroom (i.e., average = 4.175). However, statistically speaking, the difference is insignificant. In terms of academic peer-peer interactions in class, the students’ satisfaction with BlueJean is relatively low (i.e., average = 3.614). In practice, due to the limitation of Internet bandwidth and the echoes caused by adjacent computers, a vast majority of synchronous academic interactions were performed via text chat instead of video chat. In contrast, the students’ satisfaction with the online forum service (i.e., Piazza) is much higher (i.e., average = 4.140). During the 10 weeks of course period, a total of 12,298 contributions were made on Piazza by this 130 student class. With respect to the collaborative peer-peer interactions, the students’ satisfaction with Skype and email are both relatively low: Skype (i.e., average = 3.726) and email (i.e., average = 3.469). According to a separate survey of the 20 global teams [52], the top two most frequently cited challenges of teamwork are “scheduling meetings at convenient times for all students” and “lack of reliable means to hold virtual meetings”. As a result, many teams “spent tremendous time deciding what application is most productive for every team member” and “ended up utilizing chat instead of audio/video because it was much more reliable”. In regards to the social peer-peer interactions, the students’ satisfactions with both mobile messenger (i.e., WeChat) and social networking service (i.e., Facebook) are relatively high: WeChat (i.e., average = 4.096) and Facebook (i.e., average = 4.395). Furthermore, it is interesting to notice that both WeChat and Facebook were employed to facilitate collaborative interactions with respect to, for example, coordinating meetings, dividing duties, and sharing documents [42].

With respect to the impacts on the participating students’ knowledge, skill, and attitude of ICT, the highest level of agreement (i.e., average = 4.19) goes to the “attitude of ICT” (i.e., “the experience makes me more open to new ideas, information, tools, and ways of working but evaluate information critically and competitently”). Some students reflected being “overwhelmed” by the number and type of technologies they need to learn in order to succeed in this course. Guided by the Independence Axiom, the two designers had insisted on independently satisfying every FR by means of a separate DP. As a result, the number of DPs inevitably increased. For example, three separate web-conferencing platforms (i.e., WebEx, BlueJeans, and Skype) had been deployed in order to satisfy the three independent FRs (i.e., share lecture content, support academic interactions, and support collaborative interactions). By
doing so, although robustness of the ILE became enhanced, the number of technologies imposed on students also increased.

6.2 Discussion of new knowledge

Above all, the study showcases that the advanced ICTs can be leveraged to deliver global learning experience on local campuses. On one hand, a fully functional ILE is presented with sufficient details and specifics, whose practical effectiveness has been validated thorough multiple GECs. The interested readers may directly deploy it to develop their own global courses. On the other hand, the complexity of international learning, combined with, the complexity of technology-enhanced learning, demands systemic thinking. In that regards, the study prescribes some generic design methods to guide the technical and instructional design process. The interested readers may follow the process to create, analyze and improve their own technology-enhanced learning environments.

Furthermore, the study suggests that simply immersing instructors and students in a technology-enhanced leaning environment, in no way, means that they will naturally learn how to take advantage of technologies to promote peer-peer learning and facilitate international learning. Instead, the learning curve of every instructor and each student develops differently. Generally speaking, the learning curve is observed to develop according to a S-like shape. Initially, the class as a whole learns a new technology relatively slowly, and the learning begins to accelerate once some students become experts and take initiatives to teach the others. The learning curve does not always develop in an exponential growth pattern, where proficiency continuously increases without limit. Instead, a majority of students tend to quickly give up learning a new technology after 3–5 unsuccessful attempts, and seek for an alternative technology to replace the ineffective one. Sometimes, a technology may be used by the students in an unintended way. For example, to the instructor’s surprise, in addition to social interactions, many students also used Facebook to support academic interactions (e.g., discussion of difficult concepts) and collaborative interactions (e.g., coordination of team meetings). In certain cases, some students even introduced a new technology to satisfy an unmet learning need, and the instructor needed to respond accordingly to create a new learning opportunity.

Last but not least, the study makes visible the implicit connections between engineers’ disciplinary knowledge and their educational practices. A great majority of engineers become devoted to and specialized in engineering education in a gradual and progressive manner. In the transformation process, the past disciplinary knowledge plays a critical role of driving their thinking and affecting their actions. In that regards, ethnography is proven to be a useful methodology for facilitating engineering educators to systemically track their decision making process, leading to some meaningful lessons and well-documented reflections. In the past, ethnographic approach is commonly used in education in general, while it is rarely used in engineering education in particular. This study exemplifies a collaborative model between engineering educators and ethnographic researchers. By doing so, it also answers the call of redefining engineering education towards a trans-disciplinary practice [53].

6.3 Discussion of limitations

There are several limitations that should be considered when interpreting this study. First, as the paper’s title suggests, the two chief designers had followed a systemic design process to build the ILE and to develop the GEC. In other words, the design was conducted in a semi-structured instead of an entirely systemic process. That being said, it could be argued that the design methods mentioned in the study were selected on a largely subjective basis, and other design methods may be equally, if not more, applicable to guide the design and redesign. This is somehow determined by the nature of initializing a completely new education program when little, if any, past experiences can be referred. After all, when the iPodia Program was started, it was the first time ever the two designers stepped into the domain of engineering education, hence transforming themselves from an engineer to an engineering educator. The designers had nothing else but their disciplinary knowledge of design thinking to navigate an unknown pathway, which is of course not the only pathway to synthesize design method, technology-enhanced learning, and global learning.

The second limitation is that the study was conducted largely in a retrospective manner, and the design decisions were made across a long period. In other words, some pieces of information might be unintentionally missed. For example, some design decisions were made during in-person meetings without any documentation of meeting records. In that regards, a variety of ethnographic methods have been employed to retrieve as much relevant information as possible. For example, text analysis was used to analyze the designers’ emails, discourse analysis was used to understand the lecture recordings, in-person interviews were conducted to solicit each designer’s individual reflection, and a focus group interview was conducted to cross-examine reflections of the two designers on the same design decision. It should be noted that, the author Dai has been working with the two designers for many years,
which was the precondition of retrieving information in a retrospective manner.

Thirdly, the design process described in this paper should be seen as a hybrid between creating a new system and improving an existing system. During the past few years, the proposed ILE has been continuously changed, improved, and upgraded. In other words, the designers actually went through several iterations to finally arrive at the current design solution. It has long been recognized by the design community that innovative design is often characterized by an iterative process. Due to the scope of this study, the details of design iterations were not elaborated. However, by no means, it suggests that the design was a linear process without back and forth iterations.

Last but not least, evaluation of the ILE was conducted based on and hence dependent on a GEC. In other words, it is possible that students’ course experience, either negative or positive, may indirectly influence their assessment of the ILE. As explained in the introduction section, in practice, it is very difficult, if possible at all, to explicitly separate the ILE from GEC, because the former is the technical means to develop the latter, and the latter continues to impose new requirements on the former.

7. Conclusions and future works

This paper described the systemic design process of how a team of engineering educators employed a set of design methods to integrate a variety of learning technologies to create an interactive learning environment (ILE), upon which, various global engineering courses (GEC) are successfully developed. The study is intended to make two key arguments. First, an ILE could and should be treated as a complex system, and relevant design methods can be followed to guide the design and/or redesign of such a system. Second, students can obtain a reasonably effective global learning experience, being immersed within the ILE. The evaluation results clearly showed that, overall, the participating students were satisfied with both the ILE and the GEC, and the experience had yielded positive impacts on the students’ knowledge, skill, and attitude of ICT.

The future work hinges on three directions. Firstly, more relevant design methods will be employed to guide the design and redesign of complex educational systems. In that regard, the long-term goal is to develop a comprehensive design framework, which responds to the unique demands of technology-enhanced global learning. Secondly, those emerging learning technologies, such as virtual reality, mobile technologies, and learning games, will be incorporated into the current ILE. Thirdly, the synergy between design methodology and ethnographic methodology will continue to be explored in the context of engineering education.

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