International Journal of Engineering Education Vol. 33, No. 3, pp. 1018–1030, 2017
Printed in Great Britain
0949-149X/91 $3.00+0.00

Self-Directed Learning Development in PBL Engineering Students*

RONALD ULSETH
Iron Range Engineering, Virginia, Minnesota, USA. E-mail: ron.ulseth@ire.mnscu.edu

BART JOHNSON
Itasca Community College, Grand Rapids, Minnesota, USA. E-mail: bart.johnson@itascacc.edu

PBL is recognized as a model for learner-centered education. A goal of PBL is the performance of self-directed learning by the students during the solution of the problem. A recognized outcome of engineering undergraduate programs is the development of knowledge and skills necessary for the performance of lifelong learning; in other words, the development of self-directed learning abilities. This article explores the development of self-directed learning abilities by engineering students in a PBL curriculum. It aims to characterize how graduates understand and utilize self-directed learning at the juncture where they will be entering engineering practice. 27 participants were interviewed. All were at the end of their undergraduate PBL curriculum in the Iron Range Engineering program (Minnesota, U.S.). Open-ended interviews were conducted to explore the utilization of learning elements by the participants in their acquisition of technical knowledge. Interviews were transcribed verbatim and analyzed through multiple readings and the use of NVivo. Elements of self-directed learning were identified using the words and descriptions of the participants. Using their descriptions of interactions of the elements, a composite model of self-directed learning was developed. Learning theory from Illeris and the American Psychological Association are used to underpin the composite model. The outcome of the study is the insight into how PBL provides implicit development of self-directed learning abilities. This knowledge has potential value to curriculum decision makers considering the implementation of PBL, as well as to curriculum designers who would develop such curricula. The model itself has the potential for explicit instruction of self-directed learning.

Keywords: self-directed learning; PBL; lifelong learning; learning principles

1. 1. Introduction

A common question that engineering students ask when they encounter practicing engineers is "How much of the knowledge that you use as an engineer did you learn in college?". Frequently, the answer to the question is "not much". Most of the knowledge the engineer uses is industry specific, company specific, and highly specialized. The importance of the ability to continue to learn beyond college graduation is recognized by organizations concerned with engineering graduate outcomes such as the International Engineering Alliance [1] and ABET [2]. Both have outcomes related to lifelong learning, specifically addressing the "preparation" and "ability" to engage in sustained learning after college. Despite this focus on importance, there is little evidence of either explicit instruction or feedback on the development of how to become an effective self-directed learner in engineering curricula. Rather the expectation is implicit; *if the student can succeed in achieving the engineering bachelor's degree, she certainly has developed the skills to be a lifelong learner*. This lack of explicit focus on the development of the ability to perform lifelong learning as compared to the explicit focus put on the development of the other outcomes, leads to the question "How well do engineering students develop as self-directed learners?". Further, are there models of engineering education that better develop self-directed learning abilities in engineering graduates?

2. Background

2.1 Self-directed learning and project-based learning

Candy [3] describes self-directed learning (SDL) as consisting of both product and process, each of which, he again subdivides. The products of SDL are the development of *personal autonomy* and *self-management*, while the processes of SDL are *learner control* in formal settings and *autodidaxy* in natural (non-institutional) settings. Personal autonomy and self-management would be the products of having attained some level of being a self-directed learner; whereas, learner control and autodidaxy would be processes of using self-directedness in learning in formal and informal settings. If an outcome of engineering education were to have students ready to face the workplace as self-directed learners, it would be desirable to have them acquire the attributes of personal autonomy and self-management in the college learner control settings, so they can

* Accepted 4 December 2016.

learn autodidactically in their engineering workplace.

Problem-based learning is a pedagogy where students, working in groups, organize their learning around an ill-structured problem [4]. A cycle exists where the students work together in the group to identify learning goals, go off on their own to identify resources and collect knowledge, then return to the group to synthesize the knowledge. The teacher acts a facilitator on the side, coaching through questioning. There is an interaction between problem-based learning and SDL. Howard Barrows is credited with being the lead pioneer in the development of PBL at McMaster University in Canada in the 1960s [4]. Barrows and Kelson [5] identify five goals behind the design of PBL instruction. Self-directed learning is explicitly stated. The goals are the following: (1) construct knowledge, (2) acquire problem-solving skills, (3) become self-directed learners, (4) develop effective collaborative skills, and (5) enhance intrinsic motivation to learn. Thus, the act of engaging in SDL is an essential component of student learning in PBL. Whether this is implicit for the students or made explicit by their facilitators, the students are involved in the practice of SDL when performing PBL. There are several elements of self-directed learning that are directly supported in project-based learning environments. They are the following: awareness of what they do/do not know, making learning goals, planning their learning, selecting strategies, monitoring goal attainment, and evaluating learning [6]. Based on these connections between SDL and PBL, it could be hypothesized that students learning in PBL environments would develop as self-directed learners.

Researchers have quantitatively studied the link between PBL and development of self-directed learning abilities. Two conclusions have been reached by multiple groups all using the same instrument. The instrument is the self-directed learning readiness scale (SDLRS) developed by L. Guglielmino in 1977 [7] and administered to over 120,000 adults in the time since. The conclusions of the multiple research groups are twofold. First, students in traditional engineering education learning environments do not develop as self-directed learners, and second, that students in PBL environments do develop SDL abilities [8–11].

2.2 Learning theory for analysis of results

The results developed in this qualitative study will be analyzed with respect to two frameworks. The first is the Illeris triangle and the second is the American Psychological Association (APA) learner-centered psychological principles. These frameworks were chosen due to the social constructivist nature of the models. Using both models provides different perspectives which are complimentary in developing understanding. Both are presented in this section.

Illeris [12] presents a framework for learning that serves as a model through which learning theories and aspects of a learning environment can be viewed regarding their contribution to the learning process. Illeris developed a forward-looking model of learning that allows a conceptualization of the different tensions that impact learning. His motivation was to develop a concept of learning that accounts for the complex acquisition of the wide range of competences that encompass traditional knowledge and analytical skills, overview capability, life skills, professional responsibility, and attributes such as flexibility, dynamism, creativity, leadership, and more [13]. He goes on to state that for any learning to take place, there must be two basic processes in play: internal interactions involving the psychological process of acquisition and elaboration, and external processes of interaction between the learner and his or her social, cultural, and physical environments.

Illeris [12] identifies three dimensions of learning. These are content, incentive, and interaction. The content dimension refers to the competences of knowledge, skills, and understanding. It is in this dimension that learning is acquired. It is the development of cognitive ability. The second dimension is incentive, wherein the motivations for learning are considered. In a simplistic view, if we consider the content dimension to be *what* is learned, the incentive dimension would be *why* the learner wants to learn and takes into account the emotions of learning. The third dimension considers the interactions that take place during the learning: the interactions between the learner and her learning community, and those between the learner and her environment. This is the social aspect of learning and could be considered part of the *where* and *how* the learning takes place. The content dimension is annotated by cognition, meaning, and functionality. Incentive is further described by emotion, sensitivity, and mental balance. At the top edge of the triangle, the leg between content and incentive is about the individual acquiring knowledge. When moving down toward sociality, the interactions between the student and the environment are considered.

Illeris' theory is that learning takes place at the intersection of content, incentive, and interaction, or near the centroid of the triangle. Also, in Fig. 1, Illeris labels the legs of the triangle with the relevant theories of learning where developmental psychology lies between the cognition and emotion vertices, socialization theory between emotion and society, and activity theory between cognition and society.

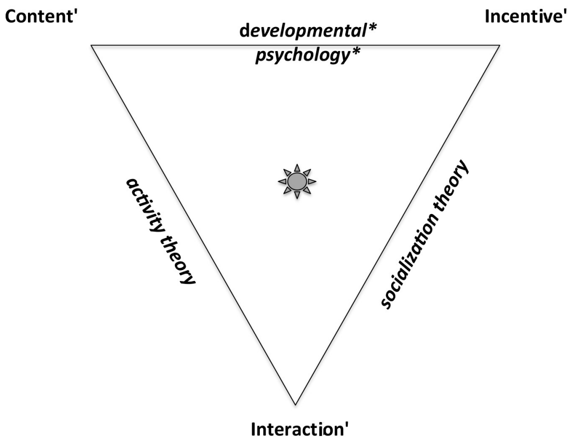

Fig. 1. Illeris Triangle [14].

Reflecting a social constructivist approach [15], in the 1990's, the American Psychological Association developed learner-centered psychological principles [16] to provide a forward-looking framework for education reform. These 14 principles are divided into four categories: cognitive/metacognitive, motivational/affective, development/social, and individual differences. The first 11 principles, when taken individually, can be placed on Illeris' tension triangle. They demonstrate importance at all three vertices and in the center. Fig. 2 lists the APA principles.

The APA took a stand saying the evidence (at the time) on learning pointed toward models that follow these principles. The principles are, for the most part, social constructivist in nature. Viewing these principles through the lens of Illeris' tension triangle shows the principles being valued in all 3 dimensions. Fig. 3 shows the APA principles superimposed on Illeris' triangle. A geographical center of the principle would be shaded to the upper left of the triangle's centroid. From our perspective, nearly 20 years after the APA principles were published, there is an imbalance in this distribution. It appears as though the APA principles, at least in quantity, did not give appropriate value to the social and environmental impacts on learning.

This criticism aside, we see value in using the APA principles, taken individually, as a way to view the learning attributes of the elements in a learning environment. The Illeris triangle and the APA principles are used to ground the results of this study and to describe the composite model of self-

Cognitive and Metacognitive Factors

1. Nature of the learning process – The learning of complex subject matter is most effective when it is an intentional process of constructing meaning from information and experience.
2. Goals of the learning process – The successful learner, over time and with support and instructional guidance, can create meaningful, coherent representations of knowledge.
3. Construction of knowledge – The successful learner can link new information with existing knowledge in meaningful ways.
4. Strategic thinking – The successful learner can create and use a repertoire of thinking and reasoning strategies to achieve complex learning goals.
5. Thinking about thinking – Higher order strategies for selecting and monitoring mental operations facilitate creative and critical thinking.
6. Context of learning – Learning is influenced by environmental factors, including culture, technology, and instructional practices.

Motivational and Affective Factors

7. Motivational and emotional influences on learning – What and how much is learned is influenced by the motivation. Motivation to learn, in turn, is influenced by the individual's emotional states, beliefs, interests and goals, and habits of thinking.
8. Intrinsic motivation to learn – The learner's creativity, higher-order thinking, and natural curiosity all contribute to motivation to learn. Intrinsic motivation is stimulated by tasks of optimal novelty and difficulty, relevant to personal interests, and providing for personal choice and control.
9. Effects of motivation on effort – Acquisition of complex knowledge and skills requires extended learner effort and guided practice. Without learners' motivation to learn, the willingness to exert this effort is unlikely without coercion.

Developmental and Social Factors

10. Developmental influences on learning – As individuals develop, there are different opportunities and constraints for learning. Learning is most effective when differential development within and across physical, intellectual, emotional, and social domains is taken into account.
11. Social influences on learning – Learning is influenced by social interactions, interpersonal relations, and communication with others.

Individual Differences Factors

12. Individual differences in learning – Learners have different strategies, approaches, and capabilities for learning that are a function of prior experience and heredity.
13. Learning and diversity – Learning is most effective when differences in learners' linguistic, cultural, and social backgrounds are taken into account.
14. Standards and assessment – Setting appropriately high and challenging standards and assessing the learner, as well as the learning progress – including diagnostic, process, and outcome assessment – are integral parts of the learning process.

Fig. 2. American Psychological Association learner-centered psychological principles [16].

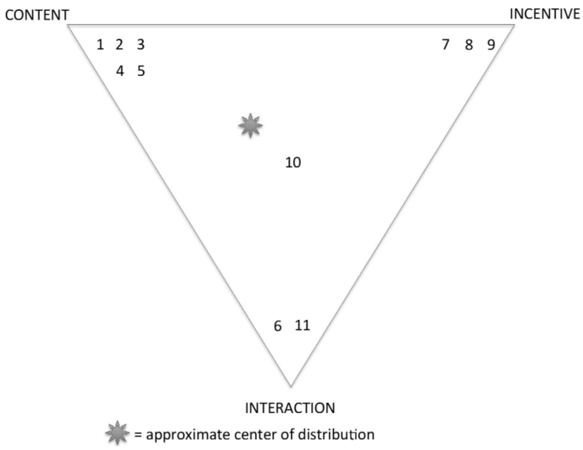

Fig. 3. Distribution of APA cognitivist-based learner-centered psychological principles.

directed learning that emerges from the qualitative research.

3. Method

3.1 Research design

This study looked to build on the quantitative results that indicated PBL pedagogies positively impact SDL development by seeking to qualitatively understand how PBL students experience self-directed learning. The location of the study was the Iron Range Engineering (IRE) program in Minnesota, United States. The IRE program is an upper-division PBL curriculum modeled after the Aalborg University (Denmark) model [17]. In 2015, Ulseth and Johnson completed a four-year quantitative study using the SDLRS instrument at Iron Range Engineering. The results confirmed that the PBL students developed SDL abilities and the traditional engineering students in comparison groups did not [18]. Upon quantitative confirmation, a qualitative study was designed and implemented.

In this study, we collected data through interviews of PBL graduates or senior students late in their last semester to understand how they executed self-directed learning. The research question that drove this inquiry was:

> How do PBL graduates implement self-directed learning?

The hypothesis, based on the connections between PBL and SDL described in the previous section was that there would be reasonably high levels of sophistication evident in the PBL graduates approaches. Data were collected from PBL students graduating from Iron Range Engineering in the 2014–2015 academic year, as well as recent graduates. Twenty-seven people participated in the study. Selecting this population allowed for a wide variety of conceptions, while still being in a range that was reasonable for the time intensive transcription and data analysis. Table 1 displays the demographic data of the participants. Each of the divisions closely parallels the overall population of the PBL program under study.

Table 1. Demographic information on participants

Demographic Category	Number
Male	23
Female	4
Under 25	17
25 and Over	10
Mechanical	13
Electrical	8
Other Engr. Major	6
Graduate in practice	15
Student near graduation	12

3.2 Data collection

Data were collected by audiotaping the interviews and transcribing them verbatim. The first questions were used to help the interviewee become comfortable and for the interviewer and the interviewee to arrive at a common language. Following the introduction, structured questions aimed at the phenomenon of self-directed learning were asked. A pilot interview was employed, as a test case, for learning how the interview process worked, vetting the interview questions, and learning from initial responses to further develop questions used in later interviews [19].

The initial scenarios aimed to look both backward and forward:

> "Think of a technical topic where you took on the greatest level of ownership in the learning. Describe the self-directed learning processes you used to complete the study."

and

> "When you practice in the engineering workforce, describe how you do/will use self-directed learning processes to acquire the next technical competence you will be required to attain."

Follow-up questions were then asked to empathetically seek out, as deeply as possible, the perspectives and experiences from the students, without imparting the views or perspectives of the questioner [19]. It is, however, necessary to recognize that the topic is jointly explored between the researcher and the interviewee [20]. The researcher must "bracket" his or her views to prevent imparting beliefs onto the interviewee [21].

3.3 Validity

Validity is addressed through the generalizability of the work and the role of the researcher. Validity can further be addressed through the use of quotes from the participants in the analysis, as opposed to only the interpretations of the researcher. In this study, quotes were extensively used to put the words of the participants front and center for the reader to interpret their thoughts.

The intent of the study was to provide knowledge for others to consider as they contemplate the implementation of PBL or the development of self-directed learning skills in students. The outcomes of the study have been purposefully generalized for use by others. The assessment of this generalizability will be determined by the extent to which others ultimately use the work.

The role of the researchers needs to be addressed for this study. We are intimately intertwined in the lives of the participants and the implementation of the PBL program under study. This intimate role is recognized for the value it might add and for any adverse effects it might have. Several steps were taken to minimize adverse influence of these relationships on the outcome of the work. The steps include the following: performing a pilot interview that was observed by colleagues, having other researchers perform some of the interviews, blinding the identity of participants' transcripts to the researchers during analysis to minimize the influence of previous shared experiences on the interpretation of results, and being explicit with the interviewees in regards to desire for openness.

3.4 Data analysis

Familiarization took place during the first read-through of all transcripts. During this phase, similarities that emerged are identified through the common descriptions participants used to described what self-directed learning meant to them. It is noted that these are the words of the participants. Emerging similarities included:

- identifying resources
- objectives/goals
- evaluation or assessment
- learning activity
- monitoring and feedback
- self-reflecting
- automation
- regulation for future
- prior knowledge
- responsibility
- schedule
- validation

Upon identifying the similarities that emerged from the first reading, NVivo queries were run to identify word frequencies, counting the number of times the SDL elements were mentioned during the interviews. The data were looked at from two perspectives: 1) in how many interviews did each of the SDL aspects arise, 2) and how many aspects did each participant mention in total. The results are shown in Tables 2 and 3.

Further keywords were queried in NVivo in an attempt to identify any further aspects that did not emerge from the first reading. Aspects that arose were: iterative process (11/27), motivation (10/27), retention (7/27), and documentation (4/27). Emerging from the qualitative study is a view of how PBL graduates identify, view, and use the elements of self-directed learning. PBL students identified 15 SDL elements. On average, they use more than 2/3 of the identified aspects. Highly utilized SDL aspects are "goal setting", "performing learning activities", "verifying results", and "seeking resources". The underutilized element of SDL is "considering the next step in learning". A second reading resulted in understandings of the ways the participants interconnected the elements.

3.5 Results

Emerging from the readings while completing the transcript readings came a composite model of how

Table 2. Number of interview participants who mentioned the aspect of SDL (27 participants)

SDL Aspect	Count	% of Total
identifying resources	22	81%
objectives/goals	19	70%
evaluation or assessment	16	59%
validation	16	59%
regulation for future	15	56%
responsibility	14	52%
schedule	14	52%
learning activity	13	48%
monitoring and feedback	9	33%
self-reflecting	8	30%
prior knowledge	7	26%
automation	4	15%

Table 3. Number of aspects of self-directed learning mentioned (11 possible)

Number of Aspects Mentioned	Count of Participants
0	0
1	0
2	1
3	5
4	4
5	4
6	3
7	8
8	3
9	0
10	0
11	0

the PBL participants interpreted and implemented self-directed learning. This composite model is composed of the SDL elements the PBL participants described. The flow of the model comes from the ways the participants described the interactions of the elements as they implement SDL in their engineering work. They frequently described an iterative nature of their learning and an intermittent monitoring. This model provides perspective on self-directed learning development of PBL engineering students. The model is developed, using the words of the participants, the way it emerged in the transcript readings.

Using the language of the participants, each component of the model is described below. It is purposeful that only the words of the participants are being used to describe these learning elements. It is being done to show that the elements are coming directly from their views.

Acknowledge motivation

"I need to have a need in my life to learn something . . . I think it's just completely stupid, . . . for me it's completely stupid to learn something if I'm never going to profit from it or use it or have like an economic reason or it's not going to make me a nicer person or something like that. Um, so I had a really hard time, I always thought it was stupid how in math we'd learn these things, you know, in the calc sequence and I don't remember them, because there was no need for me to remember them. I'm not going to feel guilty about how I don't remember them, because I never use it, you know. . . . So that was like, I guess an example of when metacognition like helps me kind of zero in on a way that I was actually able to learn new things and be excited about it enough to you know make it, to put myself in a position where I was willing to do the work to learn something." [person X]

Set goals/objectives

"First, you identify your knowns and unknowns, come up with the set of things, your goals." [person P]

Plan/schedule

". . . you create a schedule, goals, to do a list, even though you have a master schedule, you have to do this. That's daily. And then execute your goals. Make sure they're done. . . Then you, you go through the same process again cause sometimes you cannot achieve, well sometimes you can say a certain period of time and surely you can't finish that certain period of time because things, you know that things coming from all over I mean. Anything can happen, so you, you go back and analyze why didn't this finish during that period of time. Will I be able to finish it? Set up goals again and try to achieve it." [person Q]

Activate prior knowledge

". . . started reading a little deeper into those and by getting deeper into those resources they led to a lot of different resources on different levels and that knowledge, a lot of it, tied back to prior knowledge that I had had from different courses so it was necessary, I guess to tie some of that back and maybe to look up some concepts of past classes, just to refresh what was there so it tied into some other things." [person L]

Seek media resources

"then I started researching resources that, um, might have some help into that, found some books and online resources, and a few different things., um, started reading a little deeper into those and by getting deeper into those resources they led to a lot of different resources on different levels and that knowledge . . ." [person L]

Seek people resources

"I think that in my future job I'll be able to use the people that I'm working with a lot more . . . so that's probably the one resource I am excited to have available to me. I think that'll probably be my greatest resource at the beginning because they're the ones that have years of experience and knowledge." [person P]

Learning activity—Create model

"And then I would go through the process. I would gain whatever knowledge I can and whatever I don't know." [person V]

Seek feedback

"And then once, let's say you learned it then that's when you kind of go for the final, did I actually learn it, it's kind of another feedback step, but it's more defined. There should be feedback in everything, but this one is more, kind of understand what you got and if that doesn't work then you kind of backtrack and work your way through the other steps." [person F]

Elaborate on model

"I would make sure and come back through the process and figure out what I'm missing, why I missed it, and keep going through, and I think keeping reflection in that." [person V]

Practice retention activities

". . . and then you possibly reflect on it later to ensure the knowledge sticks. So some sort of using the knowledge in the future . . . this knowledge might be relied upon on the next endeavor." [person V]

Document

"I found out that in that moment that it was crucial is the writing down portion of retaining it, cause if you need to learn you need to retain it. And for me writing down really anything helped retain it. I remember I still got books, just pages, written about the cardiovascular system, um and that was a really crucial moment on really every step of the way is, that was my way for remembering and retaining it, was going over it, talking to someone and then writing it down to verify. It seemed after I wrote it down I knew it, you know. Like that, I never needed to look back at those notes. I could open up a book and look at the page and I'll be able to tell you everything I wrote in there, you know." [person E]

Monitor (efficiency, effort, alignment, schedule, personal attitude)

"So what I learned to do is that if something doesn't seem like it is going to give me any valuable information, I just kind of omit that research or those results and just say, don't spend any more time on it because it's not adding any value to my learning or my time I'm using up . . . Yeah, so it just obviously time is valuable so if in the first five, ten minutes of reading something I don't think it's valuable or adding anything to it, I'll just skip it and go on . . ." [person M]

". . . depending on how easy it was, or how you feel you know it afterwards will decide if you want to continue learning it more on your own or if you want to seek outside resources . . . before you continue further down the path." [person P]

"I would go through and evaluate which techniques, which resources that I have had or have at the moment would be able to facilitate that knowledge gain faster, more efficient." [person V]

"I've been continually like monitoring where I'm at with self-efficacy. And I haven't seen that much of a growth in that area, but what I have seen is a huge growth in like where I attribute my learning to because I, I didn't really have a good idea of where I was at as far as whether I attributed my learning too myself or to others, but I think, so I guess my growth isn't so much toward one end or the other of the spectrum, but it's just being aware of where I can get my learning from and um, where to put the responsibility at. I mean ultimately it's on myself, but if I have a good resource to go to for a teacher, seek that out, but if you don't then don't just wait around for someone to tell you um, what you should be doing." [person AB]

Verify/evaluate

"And once I reach that point I'm, I'm able to look back and see the work that I've done, . . . through notes, through discussion and then just be able to say, yeah, did I accomplish what I wanted to get, yes, I can prove it, um, no, I need to work on it because I don't have this information yet." [person N]

Regulate for future

". . . the next time I have to do one, well what did I do last time? What can I do differently? What other tools can I use instead? . . . looking back to what you did and seeing if it worked, do it again. If it didn't work, great, maybe improve it or if it didn't work at all, maybe look completely different, to do it in a different way." [person M]

3.6 Composite model

Figure 4, is a graphic interpretation of the SDL elements described above by the interview participants. To clarify, this is a composite model. No one learner explicitly identified all of the stages in this model. Rather, it is an interpretation of how learners described the different aspects of their learning, how they moved from one stage to another, how they monitored their learning while it was happening, and how they reacted to the results of that monitoring.

In this composite model, the initiation of learning begins with *acknowledgment of a motivation* to learn and a sense that without that motivation the learning need not proceed. As with most of the elements of the model, for some participants, this acknowledgment was explicit, while some just implied it, and for others it was tacit. The next steps were to *set goals* and *make plans and timelines* for the learning. At this point in the model, the learner enters a cycle that has 8 distinct stages: *activate prior knowledge*, *seek resources* (media or person), *create a conceptual model* while in the act of "doing" the learning, *seek feedback*, *elaborate the model*, *practice retention activities* to make the model stick, and *verify/evaluate* the model.

While in this model, the learner *monitors* several aspects of her learning, just as a driver might monitor her speed, fuel level, oil pressure, distance traveled, etc. on the dashboard of her car. When the driver notices the speed is too high, she slows down. When the fuel is low, she changes route and seeks a fuel station. When she has traveled a certain distance, she looks for the appropriate turn on another road. Similarly, the learner is also monitoring a *"dashboard"*. She checks to ensure her *effort* and *work efficiency* are at desired levels. She checks to ensure that the work she is doing is *aligned with the goals* she set. She monitors her *satisfaction* with the learning process, and she compares her progress with the *timelines*. Just as with the driver, when the dashboard indicates a need, she may make adjustments to the timeline, plan, or goals. She may decide to exit the learning cycle. Or, she may use this input to revisit one of the stages of the cycle for further work. For example, a learner, who is working in the creation of the conceptual model and "checks the dashboard" to see that there is misalignment between the current model and the learning goals, may cycle back to seek more resources.

Many of the interview participants identified the iterative nature of their learning, expressing that they would go through steps multiple times, advancing the sophistication of their learning until they were satisfied. Thus, the model has curved arrows showing that returning to one, or several stages is an option at the end of each stage. Further, they identified the need for documentation in nearly all stages of their learning cycle. This put documentation in the center of the learning cycle to be recorded, as appropriate, by the learner.

There is no distinct place in the cycle to exit. The learning cycle ends when the learner has reached an appropriate level of satisfaction, or dissatisfaction, or has exhausted the time available. A learner may have gone around the cycle many times or, perhaps, only partly around. Upon exiting the cycle, the learner may take the opportunity to reflect on the

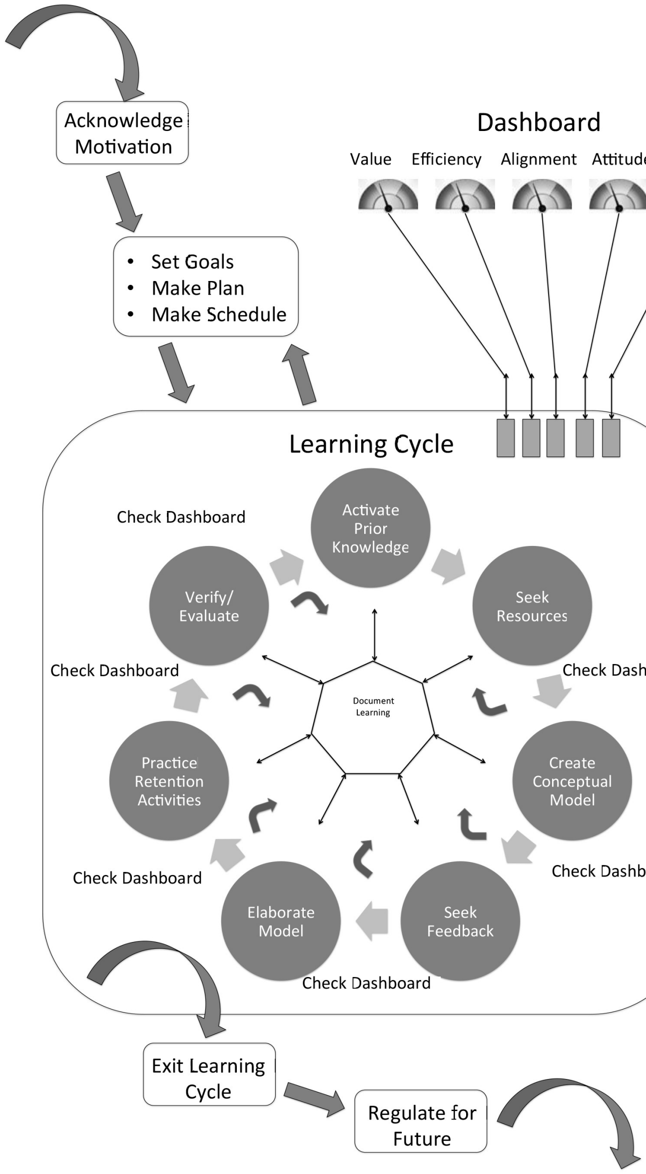

Fig. 4. Composite model of self-directed learning experienced by PBL graduates.

learning processes that were used, and regulate for future learning.

4. Discussion

This composite model has the potential to provide value for people considering how PBL implementation impacts students' perspectives and how instruction may address those perspectives. This composite perspective may also serve as a model to be used in instruction or for individuals looking to explicitly perform self-directed learning. This analysis can serve to find missing elements in the SDL model experienced by this PBL participant group and make suggestions for improving the model. Following are the components placed on the Illeris framework, each of the APA principles applicable to models of learning (1-11), analysis of how the various aspects of the composite model identify with the principle, and potential improvements to the composite model based on the principles.

4.1 Illeris triangle placement of composite model elements

Figure 5 has each of the aspects of this composite model shown on the Illeris framework. The majority of activities is cognitive/metacognitive and placed towards the content vertex. The act of monitoring using the "dashboard" leans towards incentive. In this model, there is interaction as the learner seeks people resources, seeks feedback, and seeks validation. This graphic shows there may still be remaining need for more interaction.

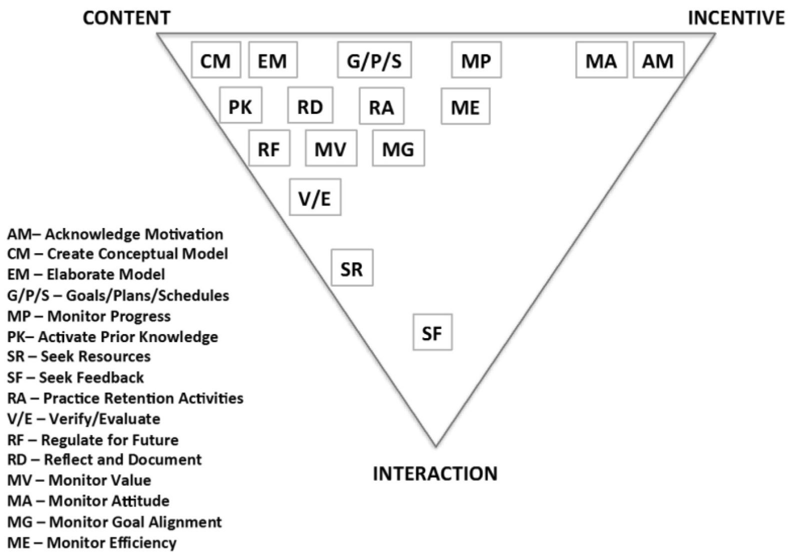

Fig. 5. Placement of Composite SDL model elements on Illeris Triangle.

These results show how the model fits on the tensions between the cognition, incentive, and interaction vertices. The self-directed learning model leans towards cognition, as perhaps it should. SDL is a component of the overall PBL model focused on the individual learning of technical content, which is a highly cognitive endeavor. The other aspects of the PBL model, such as design and professional learning, show how the overall PBL engineering learning experience does provide more balance towards incentive and interaction.

4.2 APA learner-centered psychological principles and composite SDL model

Following are descriptions of how the elements from the composite model align with the learner-centered principles. Interview quotes are used to further clarify the connections. There are places where the principles are not evident in the SDL model. This highlights potential improvements for the model for future use.

Nature of the learning process (APA-1)—The explicit act of using a model like this is what makes the process intentional for the learner. The model elements most aligned with this principle are *acknowledge motivation, create conceptual model, and elaborate on model.*

> ". . . for myself, just being able to use (SDL), being able to take advantage of any kind of learning experience that I can get ahold of . . . if it's something that I want to know about or if it's something that I need to know about, I can say with confidence to my boss or myself; I can say yeah I can figure that out. Give me some time. It will take x amount of time probably, but I can figure that out. It can be done." [person A].

Goals of the learning process (APA-2)—The acts of *setting goals and making plans and schedules* enable the learner to strive for and *monitor progress* towards meaningful representations of their knowledge.

> ". . . like I said the front end of it was, I wrote down a list of things that, different takeaways, that I really wanted and wanted to understand more deeply and kind of even broke those down into what I thought I could understand about those." [person L]

Construction of knowledge (APA-3)—The learner *activates prior knowledge* and *seeks resources* to link new information with existing knowledge in meaningful ways when creating a *conceptual model.*

> "Get a good idea of vocabulary, keywords that are used and see what it's related to, be able to understand what, what types of subjects are associated with it to get a good idea of what exactly I'm expected or required to learn. Um, once I've done that, if I can explain it or relate it to, so this is like fluids for example, this is like Archimedes principle or you could just name some other physics law that relates to it and then build from there." [person T]

Strategic Thinking (APA-4)—To achieve complex learning goals, the learner uses thinking and reasoning strategies while *creating and elaborating* their *conceptual model.* These strategies extend to the encoding the learner performs while *practicing retention activities.*

> "So I'd kind of reflect back at night and then wake up in the morning and go back and open up to the pages that I said I needed to study more and open and then just like from what people told me the day before and bring it over to the new pages and go back and reflect on the old pages."[person R]

Thinking about thinking (APA-5)—Through intentional reflection, the learner performs metacognitive activities while *documenting learning*, *practicing retention activities* and *regulating for future learning*. Further, any act of monitoring the learning during learning is metacognitive. Thus, checking the "dashboard", and any regulation that comes from the checking, is also thinking about thinking.

> ". . . adding in a check for how am I progressing through this objective, or to this objective um, what, what's going well, what's not going well, what can I change to improve this learning. So I guess during the actual implementation of learning between finding resources, making a plan, implementing it, there's the monitoring that is a continual loop." [person I]

Context of learning (APA-6)—Missing, in the composite model created as participants described self-directed learning and their implementation of it, was the management of and interaction with environmental factors. The model can be improved by accounting for these contexts.

Motivational and emotional influences on learning (APA-7)—The composite model acknowledges motivation and monitors value, goal alignment, and personal attitude. An explicit monitoring of motivation could strengthen the model.

> "I'm in structures, which is something that interests me greatly so I kind of read more in depth. . . I spend more time. As long as it interests me I spend a lot more time in it. I go a lot more in-depth" [person M]

Intrinsic motivation to learn (APA-8)—Intrinsic motivation factors, as described by the APA, include: "tasks of optimal novelty and difficulty, relevant to personal interests, and providing for personal choice and control". This is connected to Deci and Ryan's [22] self-determination theory as described in section 5.1 where competence, connectedness, and autonomy are shown to impact motivation to learn. The composite model, accounting for the *monitoring of motivation and attitude,* partly addresses these contributing factors to intrinsic motivation, though a more explicit monitoring of difficulty may expand the sophistication of the model.

> "I've been continually monitoring where I'm at with self-efficacy. And I haven't seen that much of a growth in that area, but what I have seen is a huge growth in like where I attribute my learning too because I, I didn't really have a good idea of where I was at as far as whether I attributed my learning to myself or to others, but I think, so I guess my growth isn't so much toward one end or the other of the spectrum, but it's just being aware of where I can get my learning from and um, where to put the responsibility at. I mean ultimately it's on myself, but if I have a good resource to go to for a teacher, seek that out, but if you don't then don't just wait around for someone to tell you what you should be doing." [person AB]

Effects of motivation on effort (APA-9)—Self-monitoring of effort was not addressed by the participants, but would be an improvement to the composite model.

Developmental influences on learning (APA-10)—From the APA "learning is most effective when differential development within and across physical, intellectual, emotional, and social domains is taken into account". The differential developmental influences are inherent in the entire composite model. The focus on the model is self and how the individual can choose to use her own path through learning. This is based on her level of development and on her interaction with the attributes of the learning process and her own satisfaction with and motivation for learning.

> ". . . the first thing is having an objective so something that you need to learn or a goal um, or I guess what you want to learn. And then finding out, I guess the background information or a starting point for what you're trying to learn and I guess unknown unknowns would be bad so finding out what you don't know because it's hard to learn something if you don't know what you don't know. And then coming up with some strategy or plan to learn the information, whether it's online course, through an instructor, asking a question or a coworker who knows, then finding, or I guess finding a resource and uh, then carrying out. I guess it is a post-learning, figuring out that you know it correctly and you didn't learn it wrong is probably important and then identifying if there's still things that you don't know and if you need to learn those things as well or where you're going to go in the future, or if you have enough information for what you're looking for." [person I]

Social influences on learning (APA-11)—The composite model, as described by participants, accounted for interactions with others as the learner *seeks people resources, seeks feedback, and performs verification/evaluation.* While the participants acknowledged these connections, they did not acknowledge the importance of social interactions in the learning process, nor did they consider monitoring the social aspects of learning. The model could be improved by adding a monitoring of social interactions in the "dashboard".

> ". . . then, if I do keep getting stuck there, I will go find help because self-directed learning that I've learned over the years isn't always by yourself. It is something that if you do get caught up, you need to find somebody who has more experience in that area than you, someone who can help you" [person R]

> ". . . was going over it, talking to someone and then writing it down to verify. It seemed after I wrote it down I knew it, you know. . . And that's really kind of the final step and the validation, of course, was talking to Dr. Dan." [person E]

These results show how the composite PBL model is

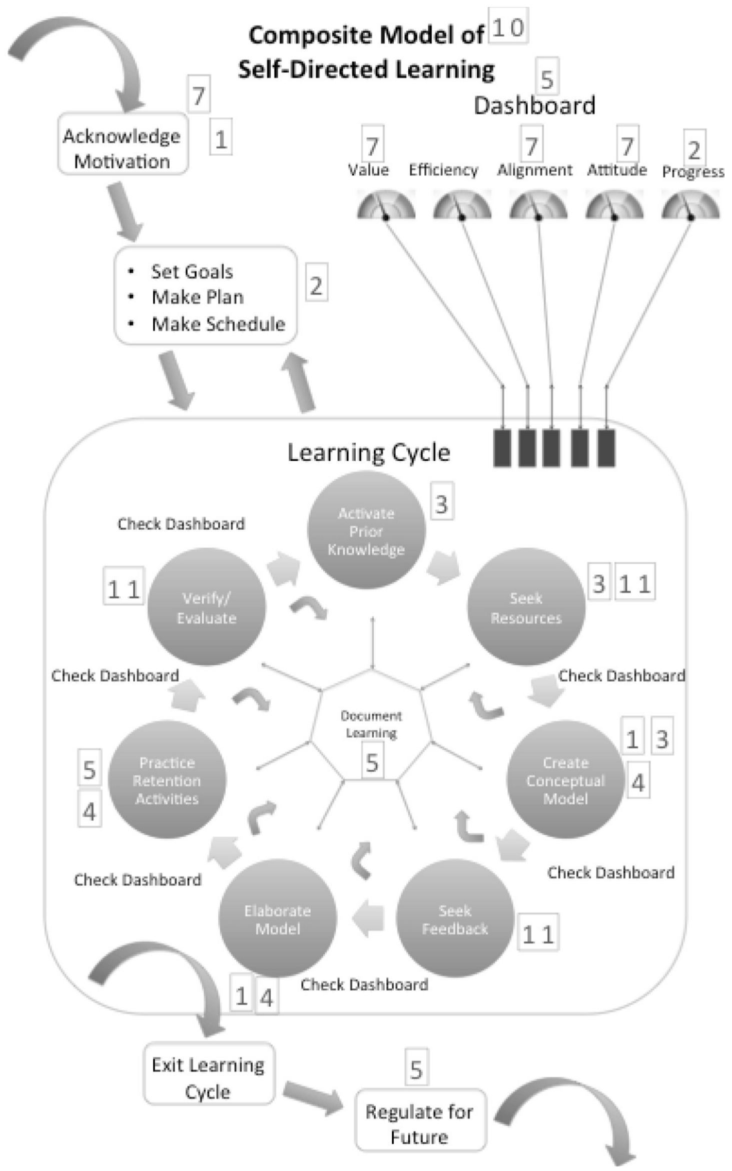

Fig. 6. Placement of APA learner-centered principles on SDL composite model.

analyzed as viewed through the 11 aspects of learner-centered principles. Fig. 6 shows how each element of the model is connected to one or more of the principles. However, there were aspects of the learner-centered principles that were not indicated in the model. These are managing and monitoring interaction within environmental contexts, as well as explicit monitoring of motivation, difficulty, effort, and social interactions on the dashboard. To use the model for the potential development of students' SDL skills, these improvements could be made.

4.3 Critical reflection and future work

A critique of this work is that the participants of this study were graduates of one PBL engineering program while the results are being generalized to all PBL curricula. Another critique would be the intimate relationship that the researchers had with the program under study and the research participants. Further, a missing element in the study is the characterization of how non-PBL students develop and utilize SDL abilities. Each of these criticisms point to potential future work. The researchers could perform a similar protocol at another PBL institution and on students graduating from traditional engineering programs. These studies would broaden the perspective of PBL graduate development and would make the visible the differences in how PBL vs. non-PBL graduates could be characterized. It would also mitigate any adverse effects caused by the intimate relationships.

Further planned future work includes an elaboration of the model adding in the missing elements identified during analysis. This model can then be tested in its efficacy for explicit instruction of SDL elements during PBL learning activities. This could be done as part of a design-based research model or action research model.

5. Conclusion

In this work, we have presented a position that self-directed learning is an essential outcome of an engineering education. Further, we have posited that learner-centered models, such as PBL, are better positioned for student development of the SDL abilities. From the literature, SDL and PBL were defined and connected. Social constructivist learning theories from Illeris and the APA were established as a framework for analyzing how PBL students experience SDL. From the literature and our own work we presented the quantitative data that demonstrate PBL students develop SDL readiness contrasting with traditional engineering student lack of development. For this current study, the research question was: "How do PBL graduates implement self-directed learning?" A qualitative study design was described, as were the methods for data collection and analysis. Through the descriptions of how they implement self-directed learning, PBL participants identified a broad set of elements and processes. The interpretation of these resulted in a model of SDL that has the potential to be used by curriculum decision makers, curriculum developers, facilitators looking to guide SDL development of students, or by individuals looking to improve their own SDL abilities. We hope that this work provides focus on the important outcome of self-directed learning and provides valuable knowledge to those looking to implement PBL.

Acknowledgements—This work was supported in part by a grant from the National Science Foundation (DUE-1129293). All opinions expressed are those of the authors and not necessarily those of the National Science Foundation.

References

1. International Engineering Alliance, http://www.ieagreements.org/IEA-Grad-Attr-Prof-Competencies.pdf, Accessed 21 January 2016.
2. ABET, http://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2016-2017/#outcomes, Accessed 21 January 2016.
3. P. C. Candy, *Self-Direction for Lifelong Learning. A Comprehensive Guide to Theory and Practice:* ERIC, 1991.
4. R. Delisle, *How to use problem-based learning in the classroom*: Ascd, 1997.
5. H. Barrows and A. Kelson, *Problem-based learning in secondary education and the problem-based learning institute*, Springfield, IL: Problem-Based Learning Institute, 1995.
6. C. E. Hmelo and X. Lin, Becoming self-directed learners: Strategy development in problem-based learning, *Problem-based learning: A research perspective on learning interactions*, pp. 227–250, 2000.
7. L. Guglielmino and J. Paul, *Self-directed learning readiness scale (SDLRS),* Boca Raton, Florida: Guglielmino and Associates, 1977.
8. T. Litzinger, J. Wise, S. Lee and S. Bjorklund, Assessing readiness for self-directed learning, in *ASEE Proceedings*, 2004 American Society for Engineering Education Conference, 2003.
9. T. A. Litzinger, J. C. Wise, and S. H. Lee, Self?directed Learning Readiness Among Engineering Undergraduate Students, *Journal of Engineering Education*, **94**, pp. 215–221, 2005.
10. S. Jiusto and D. DiBiaso, Experiential Learning-Environments: Do They Prepare Our Students to be Self-Directed. Life-Long-Learners?, *Journal of Engineering Education*, **95**, p. 195, 2006.
11. R. A. Stewart, Investigating the link between self directed learning readiness and project-based learning outcomes: the case of international Masters students in an engineering management course, *European Journal of Engineering Education*, **32**, 2007, pp. 453–465.
12. K. Illeris, *How we learn: Learning and non-learning in school and beyond*: Routledge, 2007.
13. K. Illeris, Towards a contemporary and comprehensive theory of learning, *International Journal of Lifelong Education*, **22**, 2003, pp. 396–406.
14. K. Illeris, *The three dimensions of learning*: Roskilde Universitet, 2002.
15. D. H. Schunk and F. Pajares, Self-efficacy theory, *Handbook of motivation at school*, pp. 35–53, 2009.
16. P. A. Alexander and P. K. Murphy, *The research base for APA's learner-centered psychological principles*, 1998.
17. R. M. Marra, B. Palmer, R. Ulseth and B. Johnson, The Iron Range Engineering PBL Curriculum: How Students Adapt to and Function Within PBL, *PBL across the disciplines: research into best practice*, 2011, p. 123.
18. R. R. Ulseth and B. M. Johnson, Self-Directed Learning Development in PBL, *Global Research Community: Collaboration and Developments*, 2015, p. 48.
19. L. B. Limberg, Phenomenography, in *The SAGE Encyclopedia of Qualitative Research Methods*, L. M. Given, Ed., ed Thousand Oaks, CA: SAGE Publications Inc., 2008, pp. 612–615.
20. F. Marton, Phenomenography—a research approach to investigating different understandings of reality, *Journal of Thought*, 1986, pp. 28–49.
21. L. Mann, Ways of experiencing sustainable design: A phenomenographic approach, *Doctoral dissertation*. University of Queensland, Brisbane, Australia, 2007.
22. R. Ryan and E. Deci, Self-determination theory and the facilitation of intrinsic motivation, social development and well being. *American Psychologist,* **55**(1), 2000, p.68.

Ronald Ulseth is the Director of the Iron Range Engineering program. He teaches engineering design, professionalism, thermodynamics, fluid mechanics, statics, dynamics and physics in IRE's upper and lower division programs. Ulseth has been teaching engineering since 1989. He has a B.S. in Civil Engineering from the University of North Dakota, an M.S. in Mechanical Engineering from the University of Central Florida, and is in the final stages of earning his Ph.D. in Project-Based Learning from Aalborg University. He is a retired Commander in the U.S. Navy Reserve where he served for 25 years as an Engineering Duty Officer.

Bart Johnson is the interim Provost of Itasca Community College. Prior to his administrative appointments, he taught primarily lower division mechanics-based engineering courses from 2004 to 2013. During the past 10 years, he has been active in engineering education research through development and evaluation in the following areas: learning communities, professional competencies, self-directed learning, engineering design, and project based learning, He has a B.S. in Mechanical Engineering from North Dakota State University, a M.S. in Mechanical Engineering from the University of Michigan, Ann Arbor, and is in the final stages of earning his Ph.D. in Project-Based Learning from Aalborg University. His industry experiences include engineering positions at Whirlpool Corporation and John Deere.