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Exploring the impact of project-based mechatronics course design on alumni's entrepreneurial career pathways

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Abstract

Engineering education can influence students' entrepreneurial interests and career intentions. Furthermore, well-educated founders start the most successful tech companies. However, there is limited research on how engineering education implicitly affects students' entrepreneurial intentions, skills, and career pathways.

A deeper understanding of the influence of mechatronics education from the perspective of entrepreneurial alumni will begin to fill this gap. ME218 is an in-depth mechatronics graduate-level course sequence at Stanford University that focuses on products whose functionality is increased by using an embedded microcontroller. The course is characterized by its emphasis on project-based teamwork, experiential learning, hands-on work in labs, and a strong alumni network. Even though the course sequence does not explicitly teach or focus on entrepreneurship, a survey of 500 alumni across 25 years found that some 12 percent started their own business [1].

This paper examines the impact of the course experience on its alumni's entrepreneurial interests and innovative behaviors. It is guided by the research question: *How can mechatronics education be taught and designed to contribute to the development of more successful startups and entrepreneurs?*

A qualitative research approach was employed to explore alumni's educational and professional pathways spanning a 25-year period and their subsequent career choices. Potential interview candidates were alumni of the Smart Product Design course and were (or had been) successful entrepreneurs. The course instructor provided referrals to the majority of the interviewees, while others were identified through their LinkedIn profiles. Of the 28 alumni invited to participate, 19 interviews were conducted and analyzed. Interview questions explored alumni's learning experiences and their subsequent entrepreneurial careers. A grounded theory approach was used to guide the analysis and interpretation of the interview transcripts.

The results show how mechatronics education at Stanford University contributes implicitly to entrepreneurial careers. Two overarching themes emerged: "Relevant Learnings for the Entrepreneurial Path" and "Key Course Learning Experience."Additionally, the results reveal gaps in alumni's education that needed to be filled in other ways later in their careers.

In conclusion, this study contributes to the existing literature on engineering entrepreneurship education by providing a more nuanced understanding of the relationship between a project-based learning approach in mechatronics and its influence on alumni's entrepreneurial journeys. These findings support and strengthen the foundation for future project-based courses.

1. Introduction

Entrepreneurship is a fundamental tool in dealing with social and economic challenges [2]. It drives the welfare of a society and its economic growth [3]. Mechatronics and robotics startups are of particular interest in this field. Mechatronics provides the glue between hardware, electronics, and software and contributes to our modern society [4]. Universities support this trend and develop new courses supporting mechatronics education.

The mechatronics course sequence ME218 at Stanford University is an example of an engineering course that seems to influence its students' entrepreneurial tendency and success implicitly. Even though entrepreneurship education not being part of ME218, this project-based class seems to prepare students well for a successful entrepreneurial career. Over the last decades, several alumni started successful companies, most of them in the intersection of software and hardware [5].

Research confirms that engineering education, like ME218, can influence students' entrepreneurial tendency [6]. Well-educated founders start more successful companies [7]. There is extensive research on how entrepreneurship education for engineering students affects their entrepreneurial intentions and skills [8–17]. However, research on the implicit influence of pure engineering education on students' entrepreneurial intentions and skills is limited. Developing a deeper understanding of the influence of mechatronics education from the perspective of its entrepreneurial alumni would begin to fill this gap.

We aim to understand the long-term impact of project-based education in mechatronics. Our goal is to understand better the implicit impact of mechatronics engineering education on its alumni's entrepreneurial development. Understanding those factors will help other universities educate students in mechatronics and entrepreneurship, supporting them on their entrepreneurial journey and increasing the number of impactful innovations and startups.

Our central research question therefore is:

- How can mechatronic education be taught to lead to more successful startups and entrepreneurs?

This overarching question is answered through two more specific questions:

- What impact does ME218 have on its entrepreneurial alumni?
- What educational learnings do ME218 alumni consider valuable for their entrepreneurial careers?

We used an inductive research approach based on the Grounded Theory Method (GTM) [18–20] to find the answers. Some 19 interviewees reported their learnings in ME218 and their general education in semi-structured interviews [19, 21]. Before discussing the research method in more detail, we begin by summarizing what is known about the relationship between higher education and entrepreneurship and the basic structure of ME218.

This paper is based on the thesis "Enhancement of University Startup Support in the Fields of Mechatronics and Robotics" by Timo Bunk at the Technical University of Munich and Stanford University [22]. While the papers condense and summarize the central results, some paragraphs are adopted directly or only slightly adjusted.

2. Background and Literature Review

The literature review is divided into two parts: 1) a focus on the general influence of higher education on entrepreneurship; and 2) the relevant background for the ME218 course sequence.

2.1 Higher Education and Entrepreneurship

Most studies have found that education positively affects entrepreneurship and firm survival [23]. Students with higher education are more likely to be self-employed. Summarizing the results of several studies, Jiménez *et al.* [6] show that "secondary and tertiary education increase formal entrepreneurship as a consequence of the higher self-confidence, lower perceived risk and enhanced human capital" [6, p. 205]. Those facts are supported by the fact that highly educated engineers worry less about finding employment if their business fails [6].

Most research on the impact on students' entrepreneurial intentions and skills focuses on the effect of entrepreneurship education [8–15, 17]. However, some research on the effects of general engineering education on students' entrepreneurial motivation exists. For example, higher education increases the chance that individuals start a company and influences entrepreneurial intentions and entrepreneurial performance. Some 70 percent of founders rate their education as important for their entrepreneurial success [24]. Especially in digital startups, university education has a considerable influence on performance [25]. While general higher education leads to benefits, business and engineering education do so in particular [25]. The findings of Ratzinger *et al.* [25] "[…] indicate that human capital, in the form of higher education, has a heterogeneous influence on high growth startup performance in the form of reaching equity investment" [25, p. 774]. This may be because well-educated entrepreneurs may have advantages in discovering and exploiting opportunities [6].

Next to general education, the particular university seems to matter. First Round [26] found that teams with at least one co-founder who attended one of the Ivy League Universities plus Stanford, MIT, or Caltech performed 220 percent better than other teams [26]. Interestingly, though perhaps not surprising, more than half of all ventures started by entrepreneurs with academic education are operating in the high-tech industry. In contrast, non-academic founders mainly start companies in the production and service sector [7].

As presented, there is general research on the effects of education on individuals. Still, research on individual non-entrepreneurship education elements that influence entrepreneurial behavior and intentions seldom occurs. Engineering education's tangible impact on entrepreneurial intentions and activities is still under-researched [6]. Therefore, we aim to research the impact of mechatronics education (particular ME218) on Entrepreneurial Alumni.

2.2 The specific course's alumni being studied

Before discussing ME218, it is essential to understand what mechatronics means. Mechatronics consists of the word combination "Mechanics" and "Electronics", which also describes what it is all about: An interdisciplinary engineering craft right in the middle between mechanical, electrical, and computer engineering [27]. Nowadays, mechatronics is a crucial element of everyday life, an indispensable part of small wearables to large computer-controlled machines [4].

ME218 incorporates a Project-Based Learning (PBL) pedagogical approach. Guo *et al.* [28] refer to PBL as an "inquiry-based instructional method that engages learners in knowledge construction by having them accomplish meaningful projects and develop real-world products" [28, p. 2]. Students must cooperate to find solutions to predefined problems during the creation process.

Since our research is focused on ME218 alumni, it is essential to understand the complete course series, its content, and its context in the university. Edward (Ed) Carryer has taught ME218 for graduate students at Stanford University since 1992 [29]. Most students taking the course series across three ten-week quarters have a background in mechanical engineering. ME218 focuses on three key areas: Electronics, Software, and Actuators, to supplement and expand students' knowledge. In the beginning, students learn to take "command of the basic electronics necessary to design and build mechatronic systems" [30, p. 6], followed by programming microcontrollers and understanding data sheets to work with new microcontrollers independently. Because of the steady development of technology and mechatronics, Ed Carryer updates the course every year. After completing the course sequence, students should feel comfortable applying their mechatronics knowledge to real-world problems. [30]

The ME218 philosophy at Stanford University is built on the following ideas:

- "Mechatronics is fundamentally about integration
- Building is essential to taking command of the material
- Modern Mechatronics is not a solo activity
- Collaboration is essential in building complex systems
- Community is important to establishing lifelong connections
- Projects should have an element of Whimsy or Wow" [30, p. 12]

ME218 strongly focuses on applying this philosophy in the lab, combining theoretical knowledge with direct implementation. Each quarter includes a project where three to four students work in teams to solve an exciting challenge. The course environment leads to a sense of community that persists long after graduation.

Understanding how the course influences students is vital to understanding how ME218 encourages innovation, an essential part of entrepreneurship. For this reason, Ed Carryer focuses on three main points:

1. “Always emphasize problems for which there is no one ‘right’ solution.
2. Class-wide team projects
3. Model innovation on the design of the projects” [30, p. 8]

ME218 alumni are spread all over Silicon Valley and worldwide and can be found in the world’s most successful companies. In addition to those alumni in impactful roles at successful companies, other alumni have leveraged their experience and knowledge to found startups; a survey of 500 ME218 alumni across 25 years found that some 12 percent have started their own business [1]. However, while seeming very influential, the impact of the project-based coursework in mechatronics on its alumni has not been researched. Especially since the connection between those students’ mechatronics education and their entrepreneurial activity is unknown. This research investigates how project-based mechatronics courses can lead to entrepreneurial careers and enhance technical and entrepreneurial skillsets. It narrows the research gap between the ME218 curriculum and its implication for alumni’s engagement in entrepreneurial activities. Additionally, it identifies the most impactful elements of the course sequence.

3. Methods

Our research approach is based on the Grounded Theory Method (GTM). The interview method, including the data collection and analysis processes, will be explained in detail in the following section.

“The procedures of grounded theory are designed to develop a well-integrated set of concepts that provide a thorough theoretical explanation of social phenomena under study.” [18, p. 5]. Thereby, GTM provides procedures to construct theories from qualitative data. Corbin and Strauss [19] recommend GTM to “gain new insights into old problems as well as to study new and emerging areas in need of investigation” [19]. GTM can be used to examine aspects of behavior and identify influence factors in under-researched fields. Therefore, the initial situation combined with the research questions is a precise fit for GTM. To encourage originality and to “[…] generate new concepts and grounded theories […] via qualitatively rigorous inductive studies […]” [20, p. 26], we utilized the inductive research method presented by Gioia *et al.* [20]. This approach is also aligned with Schreier [31], who recommends inductive category development to stay as near as possible to the interview material [31].

Following GTM, we used a theoretical sampling approach. Theoretical sampling is a “method of data collection based on concepts derived from data” [19]. Theoretical sampling gives guidance on collecting data to make a significant contribution to research. Unlike other conventional methods, theoretical sampling provides researchers with more flexibility in the data collection process and enables them to explore concepts in depth [19]. The theoretical sampling approach recommends choosing a sample population with the most theoretical insights to extend the theories and answer the research questions [32].

Following the foundations of theoretical sampling, we defined the criteria for recruiting potential subjects focusing on the influence of project-based mechatronics education on alumni's entrepreneurial development. Entrepreneurial alumni of the project-based mechatronics course ME218 at Stanford University were especially suited as a sample group. ME218 has been offered continuously since 1992 by Ed Carryer. Therefore founders of different ages and experiences were identified and recruited for the interviews. Various startups in different fields were also included to get a broader view.

Following the prerequisites mentioned above, the interview recruiting criteria was defined as:

- Being a ME218 alumnus while Ed Carryer was teaching ME218
- Holding a (former) founder or co-founder position
- Contributing to gender balance
- Contributing to generational balance
- Contributing to variation in industry

Potential interview candidates were ME218 alumni and were (or had been) successful entrepreneurs. The course instructor provided referrals to the majority of the prospective interviewees, while others were identified through their LinkedIn profiles. Course alumni scheduled an appointment with the research team using Calendly. This calendar tool provides the interviewees with all crucial information about the study and seamlessly helps them plan a meeting. Of the 28 invited alumni, 19 completed the interviews. A semi-structured interview protocol was generated to compare the interviews most efficiently. Following GTM and the advice of Corbin and Strauss [19], the semi-structured interview guideline was revised and refined several times during the interview process. The interview protocol consisted of an intro, six main sections, and a wrap-up section.

All interviews took place in a one-on-one setting with the camera switched on using the Zoom video conferencing tool. The average duration of the interviews was 47 minutes (ranging from 28 to 63 minutes), leading to a total of nearly 15 hours of audio material. Following the interview, all interviews were transcribed using the web-based transcription tool Trint, and the transcripts were manually revised following a denaturalized transcription approach [33]. Afterward, all interviews were anonymized to protect the interviewees' privacy and reduce bias in the analysis [20]. However, this interview data alone does not create any value but requires analysis and interpretation of its qualitative content. Qualitative data analysis is especially suited for identifying common patterns in interviews [34] to derive meaningful and data-driven.[31].

Demographic information on the 19 interviewed alumni is shown in Table 1. The distribution between 17 male interviewees (89%) and two female interviewees (11%) does not seem evenly distributed. However, those numbers are closely aligned with the nine women identified within the total 132 candidate subjects, which means that only 7 percent of this group are female founders.

Some 79 percent of the interviewees were still in a founder position at the time of the interviews. In contrast, others focus on investing, searching for new opportunities, or holding senior positions in other companies. More than half of the interviewed founders graduated between 1995 and 2004. Roughly half of the interview population started their venture directly after university without experience in full-time employment. The impact of ME218 and the link to mechatronic-related topics can still be found in most startups. Some startups left the hardware side and shifted into developing pure software solutions.

Table 1: Descriptive Characteristics of the Research Sample

		Number	***%***
Currently in Founder Position (not founder of a VC Fund)	Yes	15	78.9
	No	4	21.1
Gender	Male	17	89.5
	Female	2	10.5
Graduation Year from Stanford University (Highest Academic Degree)	1995-1999	4	21.1*
	2000-2004	2	10.5*
	2005-2009	6	31.6*
	2010-2014	5	26.3*
	2015-2018	2	10.5*
Work Experience before founding (> 1 Year, not parallel to university)	Yes	10	52.6
	No	9	47.4
Usage of ME218 Technology (Software & Hardware)	Yes	14	73.7
	No	5	26.3

4. Results

This section presents the main results of the qualitative data analysis process based on 19 conducted interviews. The results include the interviewees' experiences and learnings during ME218, their general education, and aspects they wish they had learned at university. These results concentrated on findings that arose in a number of interviews to avoid sole opinions. Illustrative quotes are included in each category to make the results more graspable. Bold words and phrases indicate specific open codes frequently mentioned in the corresponding category. The quoted interviewee and the quote's position within the script are indicated in brackets after each quote. The fictitious abbreviation names protect the interviewees' identity. The "I" stands for “Interviewee,” and the numbers were assigned according to the interview order. The last letter of the abbreviation “F/M” stands for female or male. Each category begins with a summarizing proposition supported by the interviewees’ statements.

4.1 Relevant Learnings that supported an Entrepreneurial Path

This section describes the most relevant learnings and skills the interviewees acquired in their general education and particularly within ME218 that helped them in their entrepreneurial careers.

In the interviews, two essential competencies emerged related to the experience in ME218, namely the applicable mechatronic skills and solving complex problems.

4.1.1 Applicable Mechatronics Skillset used in Entrepreneurial Endeavors

> **Proposition 1.1**: During ME218, students acquired applicable mechatronics skills, which they feel comfortable applying to real-world problems.

Some 15 interviewees see their mechatronic skills as an essential takeaway from ME218. I03M said: *“ME218 gives some very good structure, a very solid foundation about hardware and software.” (I02M, Pos. 39).* ME218 alumni report a *“[…] very good understanding of how embedded systems in general work. What types of things are easy to solve with embedded systems, and what types of things are very hard to solve with embedded systems.” (I03M, Pos. 19).* ME218 teaches its student *“[…] the fundamentals of building smart machines from scratch.” (I14M, Pos. 22).* Next to the more general topics, alumni mention some specific elements of the course, for example, the *“[…] straight-up good education on circuit design […] (I10M, Pos*. 15) or acquired skills on *“[…] how to read a data sheet.”* (I10M, Pos. 16).

One of the critical elements in mechatronics and one Ed Carryer emphasizes a lot is the integration), which is, according to I13M, *“so much more challenging than anything else” (I13M, Pos. 27).* And I10M stresses this opinion*: “Actually integrating technologies, […] that is a skill all by itself.” (I10M, Pos. 15).*

The hands-on approach of ME218 ensures that students can apply and implement their mechatronics skills to their future problems or projects. I02M acquired the skills to *“[…] quickly implement some ideas from software to hardware.”* (I02M, Pos. 40). This is also the experience of I08M: *“Getting to dig deep into the systems that really drive all of our electronics. It blew my mind. It was so cool. It was actually really what helped me drive at both of the first two startups.” (I08M, Pos. 33).* I12M reports that ME218 still influences his current work: *“I am in a stage of the work that we are doing right now on this project: we are building [a consumer product] where we are actually using ME218 techniques. I am actually doing embedded systems programming.” (I12M, Pos. 21).*

Those whose path took them into a more managerial career also benefit from their mechatronics skills, as I15M describes: *“I was sitting in a session yesterday. It was kind of a lunch and learn thing. And we had someone on our team talking about the ins and outs of GPS in a pretty* *technical level […], and it comes up pretty back to 218." (I15M, Pos. 21).* Moreover, as a funny example, I19F may not actively use it in their job but still reports about her skills: *"I just repaired one of our sunroofs. […] I resoldered the whole system back together and fixed it. I fixed our fireplace too. I powered up the soldering iron. I have to say it has been one of those skills where even as an adult, many, many years out, I feel comfortable tinkering with stuff in a really positive way that I think is pretty cool." (I19F, Pos. 30).*

4.1.2 Solving Complex Problems

Proposition 1.2: During ME218, students acquire skills to solve complex problems.

According to I19F and seven others, ME218 *"[…] is a great program to teach you how to think, to teach you how to be an interdisciplinary, creative problem solver […]" (I19F, Pos. 6).* ME218 teaches *"[…] how to solve some problems that you have never seen; how to quickly solve it […]" (I02M, Pos. 33).*

This fact may come back to the ME218 teaching approach. I09M reports: *"[…] there was the huge difference between a prototype and actually getting something to work in practice. […] Will it work in a competition? Will it work multiple rounds? And that is where so many teams would fall to. (I09M, Pos. 11)*. This teaching approach *"[…] really teaches you the idea that you can sort of in a week or two […] you can sort of do the first principles thinking on how the system would come together." (I18M, Pos. 13).*

ME218 students learn how to apply their knowledge to real-world applications where there is no correct solution. "*There are infinite numbers of solutions, and it is up to you to use the tools that you have been given to solve this problem." (I11M, Pos. 23).* ME218 students learn how to disassemble complex problems *"[…] into small tasks that you can reach […]" (I02M, Pos. 33).*

Summarizing her skills in solving problems and referencing ME218, I19F said: "*I would say the other part of being an entrepreneur and now being an investor that my education gave me was the ability not to be overwhelmed by solving hard problems. And this is what I loved about Ed Carryer's class, no matter how impossible the task seemed, there were all these amazing ways to solve the problem that was brilliantly different." (I19F, Pos. 21).*

4.2 Specific Course Elements that supported Solid Technical and Problem-Solving Skills

This section summarizes the learning experience ME218 alumni shared during the interviews.

4.2.1 PBL Approach

Proposition 2.1: ME218 students value the outstanding PBL approach

Some 17 out of 19 interviewees praise and appreciate the project-based learning approach used for the ME218. I11M supports this point with the statement: *"I have had project classes before, [..] but I mean 218 does a particularly good job of it, where you actually get to learn things and* *then apply them to a real-world problem" (I11M, Pos. 23).* ME218 does an excellent job of including all key project-based learning features into the course sequence.

ME218 projects start with an **open problem** description. I11M remembers the task formulation: *"[…] here is a problem. Now you solve it; however, you decide to solve it, it is up to you and your teammates or whatever, just you by yourself." (I11M, Pos. 23).* In general, the course structure provides a good guideline. However, it is still *"open-ended enough that you get to solve practical problems" (I10M, Pos. 15).* Even though ME218 is a university course in a lab, the applications create a close link to reality. I01M describes it as: *"a very real-world example of what you would do" (I11M, Pos. 23).* This open approach continues, and according to the interviewees, the *"[…] ME218 course sequence was so valuable because it is an **extremely practical and hands-on** course sequence." (I07M, Pos. 19).*

ME218 is a highly challenging course sequence, and therefore students have to accomplish tasks they could not imagine doing before. To solve the problems, *"[…] you were forced to work in teams to be able to pull that off." (I19F, Pos. 21).* Thereby ME218 enforces a **vital teamwork** component. I10M said: *"It is a people challenge as much as it is a technical learning. That is a really fundamental thing I took away from that." (I10M, Pos. 15).*

Nevertheless, even with a strong team, students need to actively **reach out for help**, which is often provided by the ME218 teaching team or alumni of the course. I05M comments: *"And it was all about survival in the sense that you had to go talk to the TAs, talk to the professor, to the people you knew who had taken the class before, tried to gather as much information about how to crack this problem and getting things done." (I05M, Pos. 17).*

Particularly noteworthy are the **competitions and final projects** mentioned by nine interviewees as one of the key elements of ME218. I19F remembers *"[…] 218a and 218b final projects like it was yesterday. The grueling aspect of getting to that point and then having it all come together in the eleventh hour […]" (I19F, Pos. 31).* While the competitions are fun for the students, they also simulate a **real-world environment** where the technology must work reliably. I09M learned that *"[…] there was the huge difference between a prototype and actually getting something to work in practice." (I09M, Pos. 11).*

4.2.2 Extreme Challenge

> **Proposition 2.2**: During ME218, students learn to overcome extreme challenges and learn how to handle high workloads.

ME218 comes with a lot of required effort and challenges. Fourteen interviewees describe their ME218 experience as challenging, and I03M even as *"[…] the premier, the most challenging […]" (I03M, Pos. 19)* course for mechanical engineering graduates. ME218 is challenging in two ways: the **academic challenge** of solving complex problems coupled with the **high workload** and the resulting **time pressure**.

I05M describes course work in a way that *"[…] you basically were given a problem which you were totally clueless about, and you had a week to figure it out and come up with a solution and* *demonstrate a prototype." (I05M, Pos. 17)* and therefore *"[…] constantly being pushed beyond what you have done before as the year progresses […]" (I10M, Pos. 15).* I18M supports this statement: *"[…] we would typically spend three or four days prior with no sleep, all day, all night working on getting the system or whatever the project was ready." (I18M, Pos. 19).*

Showing the impact to the field of entrepreneurship, I13M summarizes ME218 as the *"[…] closest experience I have had to the pain of doing a startup." (I13M, Pos. 27)* and adds: *"My co-founder was also 218. If someone says they took 218 you are: 'OK, this guy can deal with pain.'" (I13M, Pos. 27).*

4.2.3 Feeling of Achievement

Proposition 2.3: Challenging tasks in project-based mechatronics courses with visible successful results lead to a feeling of achievement.

While the effort still sticks to the memories of the ME218 alumni, it also comes with a sense of accomplishment. *"You complain about the time, but assuming that there is some satisfying output like the competition or whatever, I think it sticks with you, and it is a fun memory." (I15M, Pos. 22).* I19F enjoyed *"[…] the sense of achievement with the final projects […]" (I19F, Pos. 31).*

This feeling may come from the generally **visible progress** during the course, as I13M describes: *"Ed Carryer will start with what is a resistor and then prototype a circuit with a resistor, and then by the end of it, you are building an autonomous hovering robot." (I13M, Pos. 23)*. However, another part of this achievement could come from the challenging tasks and the high expectations from the teaching team and the well-performing fellow students. I05M states: *"You had to deliver something. And then within a week that it had to work. If it did not work completely and it was half working, you did not pass, it was very clear, black and white, it works, or it does not." (I05M, Pos. 17).* However, after days and nights of hard work, the teams usually succeeded, as I11M describes: *"[…] we finally got it all working and the robots driving around the field, and it was doing exactly what we told it to do." (I11M, Pos. 28).* After completing ME218 and the final projects, the students realize that *"[…] it is amazing how much you can accomplish." (I01M, Pos. 34).*

I18M summarizes his feeling of achievement with the successful project outcome: *"So I think that is my big takeaway for me more than the actual learning of how to write the code and the embedded systems, but how do you do those projects which are so complex and cross-functional in these themes in a short time period, and then still have something successful at the end." (I18M, Pos. 19).*

4.2.4 Fellow Students

Proposition 2.4: ME218 attracts highly motivated and talented students and creates an environment where friendship and partnership flourish.

Ten interviewees emphasize the connections and the quality of their ME218 classmates. *“Ed Carryer will tell you on day one: ‘This is hard, and we will take up your whole life for this year.’” (I12M, Pos. 29).* Thereby he creates that feeling that the students *“[…] are all in the Marines together […]” (I15M, Pos. 22)*. The preselection process at Stanford University and ME218’s image leads to the situation that *“[…] the people around you are phenomenal.” (I01M, Pos. 34).*

During ME218, students collaborate closely and spend much time together. Their **personal relationships** and friendships stick over the years, as I12M shares: *“[…] I have probably talked to 10 alumni in the last month, just who are friends or coworkers or something. People I took this class with 15 years ago at this point or had taken the class after me in other years.” (I12M, Pos. 20)*. Beyond the personal relationships, ME218 alumni report about their **professional relationships** with other ME218 students. Several interviewees said that their *“[…] co-founder was also 218.” (I13M, Pos. 27)* or I03M shares: “*[…] people who took 218 with me, who later came and joined my startup.” (I03M, Pos. 19).*

4.3 General Education

This section summarizes the crucial learnings for ME218 alumni on their entrepreneurial journey. It covers the students’ learnings at Stanford University that helped them create a company.

4.3.1 Practical Application

> **Proposition 3.1**: Practical application and PBL are the most valuable teaching approaches for future entrepreneurs.

The first finding is not directly related to any specific learning but the teaching approach in engineering education. Some 16 out of 19 ME218 alumni put significant emphasis on practical learning, hands-on learning approaches, and real-world experience. I08M states: *“[…] the part that lit me up, that made me the most exciting was always the shop class, the hands-on experience of engineering, any project-based class.” (I08M, Pos. 38)* and I03M adds: *“I would say that those hands-on skills were absolutely crucial; the hands-on design skills and the classes I took in that lab were absolutely crucial.” (I03M, Pos. 16).* Others, like I09M, who may have had fewer practical courses, criticize that the part *“[…] missing is real-world experience, actually building stuff […]” (I09M, Pos. 19).* Especially regarding hardware skills, I07M demands to spend: *“[…] more time in the machine shop or the electronics lab.” (I07M, Pos. 52).*

Most interviewees agree that *“there is value to theory, and you need to understand a certain level of engineering and science and business and whatever if you want to be an entrepreneur, but I think just as much practice and practical experimentation as is feasible is probably a good thing.” (I07M, Pos. 19).* The application of as much practical experimentation should not conflict with theoretical learning, as the practical implications also have an impact on the motivation for studying the theory, and I08M proposes his ideal teaching approach: *“[…] it would be making sure that all of my theory classes tie into projects somehow so that I can really* *see the real-world application of it. That then makes me care about the theory and gets me excited about it." (I08M, Pos. 38).*

The practical application is also an excellent preparation to become an engineer and entrepreneur as I16F states: *"[…] at Stanford University, my experience was way more applied, and I thought that part was actually the thing that prepared me the most to start my engineering career." (I16F, Pos. 9)*. I19F mentions that this could be *"[…] because of the fact that you can see how what you are learning is actually applicable to solving current problems […]" (I19F, Pos. 57).* Practical application also generates a feeling of investing time into something useful, as I01M shows with this example: *"Stanford was very applicable. They taught me things that would be useful. I was learning them to go implement them, not learning them, because I was supposed to go learn them because the person before me learned them. It was: '[…] hey, learn this, and here is how it is useful.'" (I01M, Pos. 28).*

I06M summarizes that *"[…] project-based technical classes, where you are actually building something, are useful because they sort of provide this bridge between all the theoretical knowledge you have gotten and the real world." (I06M, Pos. 20).*

4.3.2 Design Thinking and Lean Startup Approach

> **Proposition 3.2**: Learning about design thinking and Lean Startup approaches at university benefits future entrepreneurs.

In total, fourteen ME218 alumni emphasize the value of entrepreneurship-specific learnings related to design thinking and the lean startup approach. While some interviewees had already learned about it at Stanford University, others had to learn it during the founding process. When asked about essential learnings, I19F replied: "*I think the whole **design thinking principles**. I think those are hugely important, the kind of the **user-centered design** and observation**, iteration** […]" (I19F, Pos. 21)*. Her statement is similar to what I04M values about his education at Stanford University: *"And I think the core of it, both the undergrad and the graduate programs at Stanford University, the core of it is really about taking a flexible approach to problem-solving and one that's highly iterative and very, very user-centric. So, focusing on the end-user, whatever it is you are trying to create or whose problems you are trying to solve." (I04M, Pos. 14)*. I07M shares the learning he took away from a problem-centric teaching approach: *"I am looking to solve problems that real people are having in the world, and then once I solve them, I want to let those people try it and decide if it works. I think that that is a very good habit to build." (I07M, Pos. 30).*

Interviewees emphasized the importance of finding **product-market fit**. I18M even states: *"I think it is the single most important thing that people need to learn. And I would say most people that fail in startups just do not know this idea of what is product-market fit and how to find it." (I18M, Pos. 46).*

Finding product-market fit is a challenge, and iteration is a crucial element to find it. I09M wants universities to encourage *"[…] people to have fast iteration […]" (I09M, Pos. 33)*. Education should lead to the mindset described by I11M: *"[…] if it works great, and if it does not, then take what I learned from the trial-and-error process of the scientific method and then go back." (I11M, Pos. 21).*

4.4 What might be missing

4.4.1 Business Education

Proposition 4.1: Fundamental business education benefits future entrepreneurs.

While engineering education played a significant role in most interviewees' education, nine interviewees report business knowledge as essential in an entrepreneurial career. I18M states: *"I think the things that I did not spend enough time on, which I should have, would be learning sales, finance, and accounting." (I18M, Pos. 23).* I01M seems to agree and said: *"I think finance is a much bigger part, especially as an entrepreneur, your understanding of balance sheet, cash flow statement, P&L […] especially if you want to be an entrepreneur […] it is really important to understand how they work". (I01M, Pos. 45).*

Especially in hindsight, ME218 alumni *"[…] would have taken a couple of basic business classes, just to understand." (I11M, Pos. 39).* Not having the proper business education could mean a disadvantage as for I19F: *"I went through the UNIVSERITY1 engineering program; I did not get any exposure to the business side of things or the entrepreneurial side of things. And that was a huge deficit for me." (I19F, Pos. 13).*

Even though ME218 alumni report the importance of business knowledge, they also state that it does not need to be excessive. "*Like one class of business, 101, introduction to business. […] just like the nuts and bolts of how accounting and legal stuff works […]" (I11M, Pos. 39).* While some students also see value in particular topics like *"[…] patenting things […]" (I01M, Pos. 47)* or *"[…] marketing and sales […]" (I08M, Pos. 11).* Others like I09M would keep the business education as lean as possible as it is possible to learn the business side *"[…] more easily and without sort of formal education." (I09M, Pos. 13).*

5. Discussion and Implications

Prior studies show different approaches to implementing and assessing the impact of PBL mechatronics education [35–38]. However, they mainly focus on the teaching approach itself or evaluate the short-term effects on students.

Based on our analyses, integrating the PBL approach in this mechatronics course sequence has created a technically intense learning experience valuable to future entrepreneurs. Students learn about the theory, apply it to an open problem, and master the mechatronics skill set. Students and teams support each other, and the teaching team encourages a collaborative environment. During the final projects, students create tangible products.

The competitions ME218 implements are an influential component of PBL mechatronic education. The idea of ME218 connecting a competition to the course encouraged and motivated the former students in our sample. While the literature on the experience of PBL and competitions in mechatronics education is lean, the literature suggests "that collaborative–competitive team design events promote learning and introduce students to innovative thinking and effective teamwork." [39, pp. 3-4]. Other literature on PBL in engineering states that the "[…] involved students are typically passionate about the project." [40, p. 11], which also applies to ME218 alumni.

ME218 is a challenging and demanding course with a high workload. Students spend days and nights in the lab. This goes hand in hand with students' experience at UC Santa Cruz (which offers a course based on ME218), who "[…] report putting in excess of 20 hours/week outside of class." [41, p. 38]. Students' engagement in ME218 might be above average compared to other mechatronic courses. Still, then alumni who became entrepreneurs were willing to take the time and describe it as a good investment.

Interviewees enjoyed ME218's teaching approach and PBL in general. They encourage educators to design more hands-on courses and foster practical application. The interviewees favored PLB over traditional education and stated that they acquired more practical skills than in other classes. Those findings are consistent with other engineering students' opinions [42].

Business education is not part of the standard engineering curriculum. However, in hindsight, interviewees state that basic business administration skills helped or would have helped them in their careers.

Based on the research findings and the literature, we can come up with several conclusions and recommendations:

- The interviewees are satisfied with the learning they made during ME218, and no one suggested any additional technical aspects they would have liked to learn during the course.
- According to proposition 2.1, the interviewees value the PBL approach of ME218 and encourage other courses to follow this approach.
- After graduation, alumni have the required applicable mechatronics skills (Proposition 1.1) and feel confident building products and creating companies in that field.
- While nearly three-quarters of the interviewees mentioned the extreme challenge and time effort, they did not complain (Proposition 2.2).
- Several course alumni highlighted the competition and final projects as an essential part of ME218.
- Alumni appreciate working with current technologies during the course, which gave them an advantage when starting their companies. They encourage the teaching team to keep the hardware technologies used in the course up to date.
- Concluding from the interviews, the general course structure and content do not require any significant changes. The implication for other mechatronics courses would be to follow ME218. UC Santa Cruz, for example, already did so with remarkable success [41]. However, to make mechatronics education even closer to engineering reality, some interviewees

proposed linking some of the applications closer to the real world and suggesting cooperating with the industry.

It is also insightful to interpret the alumni course experiences through the literature on entrepreneurs. For example, the literature talks about entrepreneurs being hard workers and risk-takers; ME218 gives students challenging tasks requiring long work hours. Also, because these tasks are seemingly beyond students' applied knowledge, they are forced to assess how much risk they are willing to take and decide between a "safe solution" or a "risky and perhaps more extraordinary solution." Entrepreneurs are also information seekers who "Personally seek information from clients, suppliers or competitors" [43]; in the case of ME218, students learn to reach out to the teaching team, other students, and course alumni to puzzle through making a solution that works. And finally, entrepreneurs are skilled at systematic planning and monitoring. They know how to plan by dividing large tasks into time-constrained sub-tasks and revising plans according to changing circumstances and performance feedback [43]. The project structure with check-offs and milestones contributes to teaching students those skills.

6. Conclusion, Limitations, and Outlook

Entrepreneurship is a substantial driver of the economy and society. Governments and universities aim to increase the number of successful startups in mechatronics to support positive development in this area. In this context, this paper explored how project-based mechatronics education influences alumni and how it can be taught and supplemented to lead to more successful startups and entrepreneurs. To answer this question, 19 Stanford alumni who completed the project-based mechatronics course sequence and founded companies afterward were interviewed.

Two themes emerged based on the research: "ME218 Learning Experience" and "Relevant Learnings for the Entrepreneurial Path." The first theme, the "ME218 Learning Experience," emerged from examining ME218's teaching approach from the perspective of successful founders who took this course in grad school. As a result, we identified key course elements that could improve existing mechatronics classes.

We note that the self-selected sample group that voluntarily agreed to participate in the surveys may lead to several biases and limitations. The results could suffer from survivorship bias because all interviewees were or had been working on successful startups. The study does not include the experiences and learnings of failed founders or ME218 students who did not start a company. Therefore, one cannot conclude that the interviewees' specific experiences may be generalizable to engineering students' entrepreneurial intentions or motivations more broadly.

All interviewees took the same projects-based mechatronics design course at Stanford University, taught by Ed Carryer. Therefore, the results and implications may not be generalizable to other mechatronics courses and universities. Stanford's culture and entrepreneurship-friendly environment could have biased the students by easing the startup founding process through additional support that may not be available at other universities. The equipment and support at ME218 are outstanding and could indirectly influence the students.

All findings are based on a relatively small sample group of 19 interviewees who took ME218 over a range of over 20 years. While the interviewees' general experience seems similar, the influencing factors may vary from year to year based on the choice of projects or other external circumstances. Also, the timing for starting a company based on learnings at ME218 may depend on the state of the economy or specific technological developments at that time. Interviewees may also perceive the course's impact differently depending on their role within a company.

Additional qualitative research would extend these findings by including ME218 alumni who started but failed on their entrepreneurial journey and help overcome survivorship bias. A more heterogeneous sample group, including students worldwide and within different engineering disciplines, could create a broader analysis database and contribute to more generalizable findings.

On the theoretical side, this paper contributes to the sparse literature on the intersection of mechatronics and entrepreneurship. On the practical side, this research provides practical approaches to influence future education. Redesigned lectures could help improve students' skills and increase their entrepreneurial confidence and motivation. Therefore, it contributes indirectly to the likelihood of successful startups in the robotics and mechatronics startup scene. Additionally, the learnings about ME218 provide feedback to Ed Carryer and the teaching team of ME218 and support them in implementing entrepreneurial elements into the curriculum.

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