‘Earning your Scars’: An Exploratory Interview Study of Design for Manufacturing at Hardware Startups

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Abstract

Although many design for manufacturing tools and methods have been developed, it is unclear if engineers at startups widely use these design support techniques. We interviewed twelve engineers employed at startups to better identify common practices related to design for manufacturing. Specifically, we sought to learn the design for manufacturing strategies and tools used, and the timing of considering manufacturing constraints – such as process cost and geometry restrictions – in startups’ new product development processes. Interviews were analyzed using an inductive coding approach. All interviewees viewed design for manufacturing as being necessary for a successful product launch, but the implementation of considering manufacturing constraints varied. Interviewees mainly learned of the importance of design for manufacturing through negative personal design experiences where they did not emphasize the consideration of manufacturing constraints, a process which was described as “earning scars.” Formal education was viewed by interviewees as having limited practical utility, and startups’ staffing and funding constraints contributed to informal new product development processes and design practices. We identified ten emergent informal design for manufacturing strategies employed at startups, with most strategies relying heavily on consulting external manufacturing experts. We noted only a limited use of design for manufacturing tools, such as manufacturing simulation software and cost modeling. Insights from this paper can lead to better educational practices, contribute to more contextualized advising of startups, and guide other resource-constrained design teams.

Keywords: Design for manufacturing; product development; design methods; industry studies; startup companies

Declarations

Funding: This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE-1752814. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation.
Conflicts of interest/Competing interests: The authors have no conflicts of interest to declare
Availability of data and material: Due to IRB protections, the interview data is not available online.
Code availability: N/A
Ethics approval: This research study was approved by UC Berkeley’s Committee for Protection of Human Subjects, ID 2018-10-11463.
Consent to participate: Participants were asked to provide verbal consent to participate in the interview study and to have the interview audio recorded. Participants were told that they could stop the interview or the audio recording at any point.

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1. Introduction

Considering manufacturing capabilities and cost during the new product development (NPD) process is widely regarded as an effective strategy for avoiding costly redesigns late in the development process (e.g., Ullman 2016; Ulrich et al. 2020). Providing systematic design support (including methods, methodologies, and tools) (Gericke et al. 2017) to help designers consider manufacturing constraints may be particularly beneficial in environments where funding and time during NPD can be critical to success, as is common in hardware startups. However, much of our current understanding of incorporating manufacturing into design comes from larger companies with different organizational structures and greater access to resources than is typical of startups. An improved understanding of how manufacturing considerations impact design decisions in startups can help foster more effective NPD and ultimately help more startups achieve success.

The potential impact of understanding NPD at startups is substantial: startups account for about 20 percent of total job creation in the US, and young firms play a critical role in innovative activity in the US economy (Decker et al. 2014). A variety of terms have been used in literature to describe early-stage, small, young businesses. Here, we use Ries’s definition of a startup: “a human institution designed to create new products and services under conditions of extreme uncertainty” (Ries 2011). While the number of startups created each year varies, there seems to be a generally increasing trend in the number of startups over the past decade: in 2019, the number of business establishments less than 1-year old in the US set a 25-year high (US Bureau of Labor Statistics). Startups draw a vast amount of funding and continue to pull in more and more funding from investors: in the first quarter of 2021 alone, startups in the US raised $69 billion, more than any other quarter on record (Somerville 2021).

The NPD process involves many complex and interconnected design decisions that determine the ultimate form and function of the designed product. Ulrich, Eppinger, and Yang (2020) describe the NPD process starting with planning and concept development and continuing through production ramp-up and product launch. The Product Development Management Association refers to the NPD process as a “disciplined and defined set of tasks and steps that describe the normal means by which a company repetitively converts embryonic ideas into scalable products or services" (Kahn 2013), highlighting that NPD is a structured process to create, develop, scale, and launch new products. The quality of the NPD process has a significant impact on the profitability and impact of a new product launch (Cooper and Kleinschmidt 1995). Successful and unsuccessful projects have been observed to employ significantly different prototyping strategies (Srinivasan et al. 2020), and such prototyping strategies have been linked to startup success (Nelson et al. 2019). Considering manufacturing capabilities, constraints, and cost during NPD, a practice that we refer to as "design for manufacturing" (DfM), has been cited as an effective strategy for avoiding costly redesigns late in the development process (Ullman 2016; Ulrich et al. 2020).

Startups may particularly benefit from DfM in the NPD process. Marion and Meyer (2011) found that startups that considered part cost during NPD were more effective and efficient than those that did not. Similarly, Wolff and Pett (2006) found that product improvement efforts were positively associated with company growth and profitability. Startups face limited resources like time, funding, and personnel (Marion et al. 2012), which can impact the business's success. An analysis by CB Insights found that 56% of consumer hardware startups raised initial funding through crowdsourcing sites where the median size of funds raised was just $210,000, which provided "very little runway to support hardware manufacturing, marketing, or sales costs" (CB Insights 2017). The complexity of developing hardware is such that even well-funded startups struggle, with hardware startups such as Jawbone, Juicero, and Pebble failing after successfully raising millions of dollars (CB Insights 2017). While existing literature describes the existence of constrained resources at startups, the impact of these constraints on DfM still needs to be illustrated, and the connection to product success needs to be understood. Study of startups can also provide insight for other resource-constrained design settings such as development engineering (Madon et al. 2016).

A limited number of researchers have explored NPD at small or young businesses like startups. Marion, Friar, & Simpson (2012) found that resource constraints at startups resulted in an NPD process that was more informal than the NPD processes at more established firms. These findings echo those of Skalak, Kemser, & Ter-Minassian (1997) who found minimal adoption of concurrent engineering practices at small manufacturing companies. Young organizations may have more inexperienced engineers and move through NPD differently than mature firms (Duran-Novoa et al. 2018). These studies indicate that startups may require unique DfM strategies and tools, but more confirmation is needed.

Given the lack of studies focusing specifically on startups, referring to other research on large firms is helpful. In studies focusing on large firms, input from manufacturing stakeholders and consideration of manufacturing variation are not frequently included early in the NPD process (Ettlie 1995; Thornton et al. 2000). One reason for the delay in considering manufacturing constraints in NPD is a lack of systematic design support suited for early NPD. While there are many examples of automated manufacturability systems and DfM design tools (Gupta et al. 1997), most tools require detailed geometry information and therefore are not well-suited for early NPD when the geometric details are not yet confirmed (La Trobe-Bateman and Wild 2003; Chiu and Okudan 2010).

Beyond DfM tools, many other forms of systematic design support have been described in the literature to promote better integration between design and manufacturing. Strategies such as intense manufacturing involvement, a collaborative work environment, and supplier involvement in NPD are viewed in industry as improving a product's manufacturability (Swink 1999). Early involvement of manufacturing representatives (e.g., suppliers or internal manufacturing engineers) in NPD is related to fewer design change requests (Ettlie 1995) and to improvements in NPD effectiveness and efficiency (Johnsen 2009). Other DfM strategies include using previous designs as a starting point (Eckert et al. 2005) and referencing manufacturing design rules or guidelines (Gupta et al. 1997).

In this paper, we seek to better understand current strategies for considering manufacturing constraints in NPD by conducting in-depth interviews with engineers working at startups. Specifically, we seek to answer two specific research questions: (1) How and when do engineers consider manufacturing cost and constraints during the NPD process at startups?; and (2) How do engineers' perspectives of DfM evolve as they gain experience at startups?

2. Study design

2.1 Recruitment of interviewees

Our analysis is based on twelve in-depth, semi-structured interviews. Interviewees were recruited via email through the authors' professional networks, with snowball sampling to identify additional participants. The sampling criteria for interviewees was that they either currently or formerly (within the last two years) were employed full-time by a hardware startup in a technical role. Our focus was specifically on hardware startups, where the company's mission was to develop a new physical, manufactured product for mass distribution. We defined a technical role as a role that bears responsibility for designing the physical layout of a product and for choosing how the product would be manufactured. Potential interviewees interested in participating in the study self-identified as fitting our sampling criteria during recruitment, and we additionally screened interviewees during the interview to ensure they satisfied our criteria.

2.2 Content of interviews

The in-depth interview guide was organized into four sections:

1. **Introductory questions**, including demographic details of the interviewee (e.g., screening questions, number of years worked at the company, current role in the company) and an overview of the company where they work (e.g., number of years in business, core value to customers).
2. **Education and training**, including questions about how the interviewee learned design and manufacturing in their formal education and through their on-the-job experience.
3. **Design and manufacturing on the job**, including questions about a specific recent project that the interviewee helped design that is currently being produced or will be produced soon.
4. **Use of design and manufacturing tools**, including questions about the processes, strategies, and resources the interviewee and their company use to conduct design and manufacturing.

A 60-minute pilot interview was conducted to ensure questions were easy to understand, and the interview protocol was then adjusted. After the pilot interview, twelve interviews were conducted between November 2018 and May 2019. The interviews were conducted in English over Skype or telephone call by one author. Audio recordings were made and transcribed. All but one interview lasted between 50 and 70 minutes, with the outlier lasting 35 minutes.

Interviewees were asked to provide verbal consent to participate in the interview study and to have their interview audio recorded. Interviewees were told they could stop the interview or the audio recording at any point. This research study was approved by University of California Berkeley's Committee for Protection of Human Subjects, ID 2018-10-11463. Both authors were affiliated with UC Berkeley at the time when interviews were conducted.

2.3 Coding of interviews

A range of approaches exist to guide the analysis of qualitative data, including classical grounded theory (Strauss and Corbin 1990), phenomenology (e.g., van Manen 2016), and a general inductive approach (Thomas 2006). Here, we use the inductive approach described by Thomas (2006). Our inductive approach corresponds with this study's goal of presenting and describing the most important categories derived from our data, rather than generating theory (the goal of grounded theory) and rather than richly describing the full lived experiences of individuals (the goal of phenomenology). We did not have any hypotheses or prior assumptions about the role of DfM in hardware startups, and our chosen inductive approach "allow[ed] research findings to emerge from the frequent, dominant, or significant themes inherent in raw data, without the restraints imposed by structured methodologies" (Thomas 2006).

Because detailed description of dropping, merging, splitting, relating, and sequencing categories derived from data can provide rigor and enhance transparency (Grodal et al. 2021), we describe the evolution of our final coding scheme here. We, the two authors, developed the inductive coding scheme used in this study, with multiple iterations of trial coding and refinement. For first cycle coding, we independently read a selection of interviews accounting for approximately 20% of the corpus. We used initial coding, typically employing descriptive coding to summarize key topics, and paid particular attention to interviewees' descriptions of actions and processes (Saldaña 2016). After coding separately, our initial codes were compared. We transitioned to focused coding (Saldaña 2016), eliminated codes that were not relevant to our research questions, and grouped our codes into several categories: pain points, demographics, and categories based on design process stages.

A preliminary agreement test was performed to test reliability of code applications. Discrepancies were discussed and the codebook was adjusted. Initially, we had discrete design stages (e.g., *conceptual design, detail design*) as high-level code categories because much of the corpus was interviewees' descriptions of their design activities. After preliminary coding, we found that we coded excerpts in different stages of the design process: the discrete stages of the NPD process were difficult to distinguish from each other because they were often contemporaneous. Because of this, we transitioned away from coding discrete design stages to coding a looser continuum of *design, prototyping, and testing* activities. In the final codebook, we coded activities into four general phases that were more clearly differentiable: (1) *design initiation*; (2) *design, prototyping, and testing*; (3) *mass production*; and (4) *deployment*. We divided the *design, prototyping, and testing* phases into two stages based on whether computer-aided design (CAD) models were created for a part.

During interviews, we asked interviewees about the evolution of their design practices, and so our corpus included many descriptions of lessons learned or difficulties that interviewees faced during previous designs. Initially, these were coded as "*pain points*." After comparing our different initial corpus coding, we found discrepancies in when these *pain point* codes would be applied, as these excerpts were often descriptions of a specific design activity that went badly, and it was difficult to separate our judgment of the design activity from the interviewees' perceptions. Therefore, we eliminated categories related to pain points and instead focused on *learning methods*, where a designer described learning or evolving their own design practices, therefore eliminating our own value judgment of whether an experience was negative (i.e., painful) or positive.

In our final coding, we focused on consistently categorizing excerpts' timing and associated attributes in two broad categories: (1) design activities and (2) characteristics associated with a particular engineer or company (Fig. 1). We grouped characteristics associated with a particular design or company into three categories: *designer*, *company*, and *external environment*. Importantly, this allowed us to identify interactions between these categories, e.g., how a designer's educational background (a characteristic) influenced a designer's decision to use CAD at an early stage (a design activity). All coding activities were conducted in Dedoose, a mixed-methods research web application (SocioCultural Research Consultants, Manhattan Beach, CA).

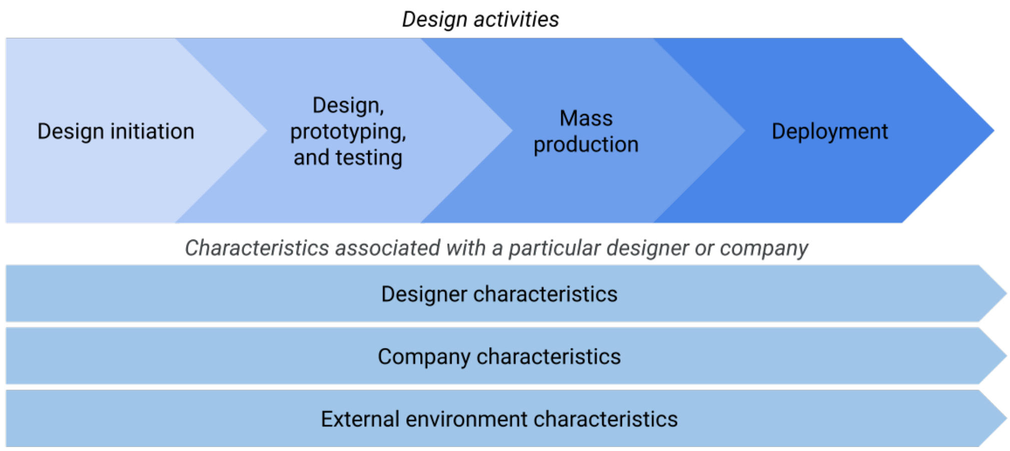

Figure 1. The final coding scheme included design activities (top) and a set of characteristics associated with a particular designer or company (bottom).

To test inter-rater reliability after the coding scheme was finalized, we used a subset of our corpus for a code application test in Dedoose. The pooled Cohen's kappa (de Vries et al. 2008) for this test was 0.86, indicating an "almost perfect" level of agreement, with individual kappa values greater than 0.70 for each of the tested codes, indicating a "substantial" level of agreement for the tested codes (Landis and Koch 1977). After this test validated the coding scheme, each author then coded half of the remaining corpus.

2.4 Analysis of interviews

After the corpus of interviews was coded, we conducted a thematic analysis (Thomas 2006). First, we summarized the basic biographical and professional information of interviewees. Then, we iteratively identified key themes across all interviews. We reviewed the coded excerpts associated with each theme to assess if they formed a consistent and coherent pattern. Once common themes were identified, we used these themes to find evidence to answer our research questions. We identified shared design strategies through analysis of key themes, with a focus on timing of when the strategy was used and the type of information utilized. Specifically, we recognized common DfM activities that were described by several interviewees in similar stages of the design process. Design activities that were described that were not conducted to gain DfM knowledge (e.g., engineering testing to determine a product's reliability) were not included as DfM activities. From these activities, we were able to identify shared DfM strategies. Each DfM strategy had a unique combination of timing and source of information, (i.e., utilizing a specific source of information to gain DfM knowledge at specific times during the design process).

After reviewing literature on classification of DfM methods, we decided to categorize each strategy based on the levels of abstraction presented by Patterson and Allison (2019): *manufacturing process considerations* (basic knowledge of manufacturing processes and their practical domains of applicability, e.g., accessibility considerations in machining); *manufacturing constraints* (moderate constraints on the use of the process in question, e.g., only being able to machine features that are robust enough to withstand heat and stress of machining), and *manufacturability constraints* (design constraints dictated by the process in question, e.g., minimum feature size). This sorting based on level of abstraction allowed us to convey an important insight: we observed interviewees employed similar strategies (e.g., consulting experts during the design, prototyping, and testing process) with distinct goals based on how specific the desired knowledge was to a particular design. By grouping strategies into levels of abstraction, we could show how designers used some strategies to obtain generalizable knowledge that could be applied to a range of similar parts and other strategies only to obtain part-specific feedback.

In our thematic analysis, we focused on what interviewees said rather than trying to recreate a history of what the interviewees actually did, to ensure our themes reflected what interviewees viewed as important in NPD. Similarly, we focused on how the engineers described dealing with manufacturing constraints and costs during the NPD process. We did not explicitly define or ask about DfM in the interview protocol, instead allowing the interviewees to use their own terminology to describe their decisions. In the rest of the text, we will refer to design decisions involving considerations of manufacturing capabilities, constraints, and costs as DfM for brevity.

3. Results

In Section 3.1, we contextualize our analysis by describing the interviewees' backgrounds and the startups where they were employed. In Sections 3.2 through 3.5, we describe how our analysis helps answer our research questions: (1) How and when do engineers consider manufacturing cost and constraints during the NPD process at startups?; and (2) How do engineers' perspectives of DfM evolve as they gain experience at startups? In each subsection, we highlight a common theme that emerged: interviewees repeatedly emphasized the importance of experiential learning for gaining DfM knowledge. In order to become proficient at DfM and NPD, our interviewees said it was necessary to 'earn your scars': to learn by making mistakes and then improve in the future.

3.1 Summary of company and interviewees' backgrounds

Table 1 summarizes the background of each interviewee, including gender, job title, degrees, approximate years of relevant job experience at the time of the interview, and characteristics of the startup at which they were employed. The startups where the interviewees were employed were mostly located in the United States (10 of 11 unique startups). Two interviewees were employed at the same "corporate startup," a small startup that was part of a larger company, operating independently of the larger company with a separate office and limited resources and staff. Most interviewees (9 of 12) worked for companies that had already shipped at least one product to be sold to customers. One interviewee worked for a large startup with approximately 1500 employees, but the other interviewees worked for smaller startups with an average of 16 employees. The average age of the startups in our sample was 6.4 years. Five startups were in the Consumer Durables & Apparel sector, three were in the Health Care Equipment & Services sector, and three were in the Capital Goods sector (using the Global Industry Classification Standard classification system developed by S&P Dow Jones Indices and Morgan Stanley Capital International).

All of the interviewees had a bachelor's degree in engineering or design and some had advanced degrees. The interviewees had an average of 6.5 years of professional experience conducting NPD at the time of their interview (although not necessarily at their current company). Interviewees fell into three job categories: design engineers, senior engineers, and CEOs and co-founders.

Table 1. Summary of interviewees' backgrounds

	Interviewee characteristics				Company characteristics		
Identifier	Gender	Job title	Degrees	Job experience (yrs)	Sector	Age (yrs)	Size (# of employees)
I1	M	Senior Mechanical Engineer	BS in Mech. Eng.	8	Health Care Equipment & Services	5	6
I2	M	CEO & Co-Founder	BS and PhD in Mech. Eng.	6	Consumer Durables & Apparel	6	11
I3	M	Founder	BS in Mech. Eng..	8	Consumer Durables & Apparel	6	1
I4	M	Senior Mechanical	BS and MS in Mech. Eng.	8	Capital Goods	2	28

		Engineer					
I5	F	CEO & Co-Founder	BS and PhD in Mech. Eng.	2	Capital Goods	3	12
I6	M	Senior Mechanical Engineer	BS in Mech. Eng.	4	Consumer Durables & Apparel	7	13
I7	M	CEO & Co-Founder	BS and PhD in Mech. Eng.	4	Capital Goods	3	48
I8	F	CTO and Co-Founder	BS in Mech. Eng.	8	Health Care Equipment & Services	5	10
I9	M	Senior Mechanical Engineer	BS and MS in Mech. Eng., PhD in Electrical Eng.	2	Consumer Durables & Apparel	10	1700
I10	M	Design Engineer	BS and MS in Industrial Design and Ergonomics	8	Consumer Durables & Apparel*	7	12
I11	M	Design Engineer	BS in Automotive Eng.	8	Consumer Durables & Apparel*	7	12
I12	M	Design Engineer	BS in Eng.	12	Health Care Equipment & Services	16	20

*I10 and I11 were employed at the same startup

3.2 Gaining DfM knowledge

Interviewees were often at different stages of the NPD process, but we asked them to reflect on the entire process in our interviews. Interviewees described considering manufacturing constraints and costs throughout the development process, but the most frequent occurrence was after CAD was created. In Fig. 2, we show frequencies of the average number of excerpts from each interviewee where they mention how they considered the impact of manufacturability or cost on the product's design. Because interviewees who had not released a product (n = 3) were still early in the NPD process, we show their data separately. Excerpts describing design, prototyping, and testing activities were categorized in two stages (pre-CAD and post-CAD) based on whether a CAD model had been created for a design. Engineers at startups that were still in early NPD described DfM considerations most frequently during design initiation, while those at more mature startups most frequently considered DfM after CAD models were developed.

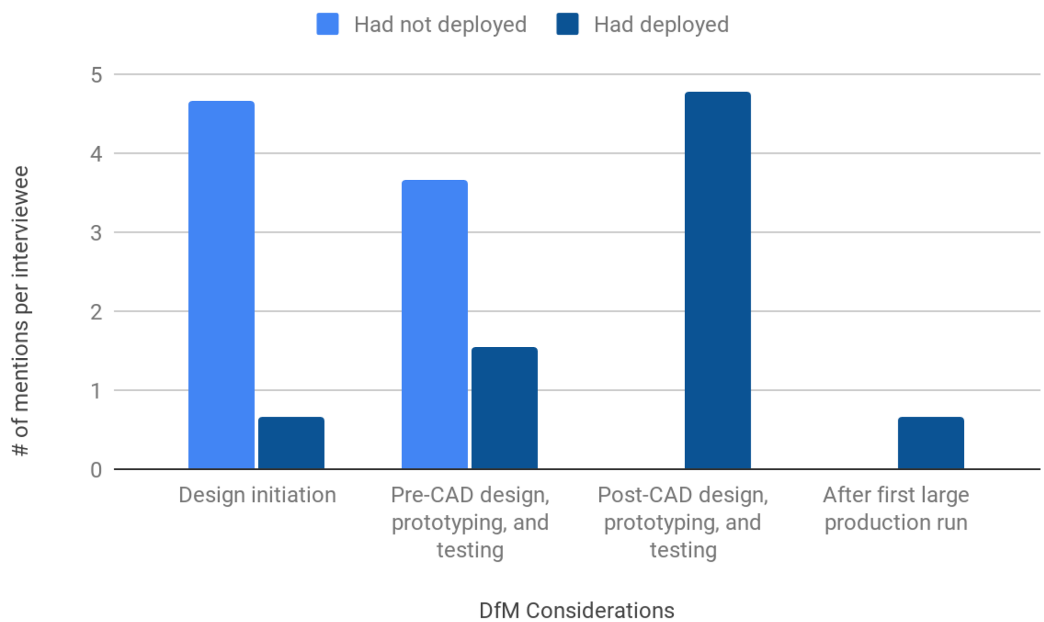

Figure 2. Interviewees who had deployed a product most frequently described making DfM design decisions after creating CAD models. Interviewees who had not deployed yet described making earlier design decisions.

Interviewees described using various sources for gathering DfM knowledge at different phases of the NPD process (Table 2). All interviewees described consulting experts (typically manufacturing vendors) to gain DfM knowledge and most mentioned learning from personal experience and formal education.

Table 2. Sources of DfM knowledge mentioned by several interviewees

Source utilized	**% of interviewees who mentioned**
Expert feedback	
-Vendors	100%
-External advisor	25%
-Network of peers	25%
-Other (e.g., design consultant)	42%
Personal experience	92%
Formal education	92%
Internet	33%
CAD-based manufacturing simulation tool	25%
Textbooks	25%
Cost model	17%

Interviewees described the increasing level of specificity of DfM sources they used throughout the NPD process. In early design stages, DfM strategies are high-level (e.g., simple heuristics and rough cost estimates), and then they gradually become more granular as more of the design is defined (e.g., detailed geometry analysis). Interviewees mentioned that they did not have enough information about their design early in NPD to complete detailed manufacturability or cost analysis.

"I kind of feel like being quantitative at the very early stage was almost useless because we don't really know what we're doing at all....As you're inventing a new process, you've got to start with a really big rule of thumb... heuristics, if you will. And then as you narrow that down, there is a level of sophistication in the calculation or the level of sophistication in quantifying things that makes more and more sense...." (I5)

We observed two distinct motivations for gathering DfM knowledge: improving understanding of manufacturing processes, and understanding how manufacturing constraints impact the specific product currently under development. Different strategies tended to be mentioned in conjunction with each of these motivations. Internet, textbooks, and formal education were perceived as better strategies to gain basic knowledge, but this basic knowledge was hard to apply to interviewees' specific design situations. Expert feedback was seen as the best strategy to gain product-specific feedback.

3.2.1 Source of DfM knowledge: Experts

Using outside experts was viewed as an efficient way to improve a design without hiring a new employee. Experts were viewed as anyone with more experience than the interviewee. Experience was seen as the ultimate form of knowledge and wisdom, and interviewees described benefitting from the experts' experiences by proxy:

"You just need to have scars. You have to have the scars of messing up, and they [my mentors] are like 'You will get those. But right now, in order to save your company, [your] startup company, you don't have the time or the money to afford those [scars]. So you need to go to someone who is quicker [...] You need to look at a guy that has seen that problem for 20 years.'" (I8)

Interviewees solicited advice from a range of experts, most frequently from potential or current manufacturing partners. Interviewees tended to refer to external companies who manufactured or assembled parts of their products using three terms interchangeably: manufacturers, vendors, and suppliers. Here, we echo the language of the interviewees in relevant quotes. Manufacturers were viewed as vital partners in a collaborative DfM process that ultimately would result in easy-to-manufacture designs. As I6 said:

"It's been a collaborative process with manufacturers. I think they've also all appreciated it. We're not like, 'Hey, here's the design. Build it.' It's, 'Hey here's the design. Let's talk about it. How can we make your life easier to manufacture it and what do you know based off your 20 years of existence that you can help feed into our design to make the end product much better for everyone?' "

Two interviewees talked about how vendors would be the best source of what was truly cost-effective and possible to manufacture, instead of other sources like the internet. Consulting manufacturers for DfM feedback was viewed as more efficient than trying to improve the manufacturability of a design without their input. For example, I1 discusses how he drew upon his experience designing medical devices products for mass production, although his current company has not yet deployed its first product:

"There's a lot of things that I have been really worried about manufacturing-wise, from reading about this online or hearing this anecdotal thing of how to design for inexpensive machining [...] A lot of that [ease of manufacturing] stuff ends up not mattering because [the manufacturers are] so good and the labor is so cheap and CNC machines are so common these days that there might be some feature where if you designed a certain way, it would be a little bit easier to make, but [the manufacturers] just don't care because it ends up not affecting the price that much or not being a real concern."

A few interviewees mentioned complications with collaborating with experts on DfM efforts. Manufacturing vendors were seen as the best people to assess manufacturability, but interviewees said they had to fight to preserve hard-to-manufacture features to ensure desired product aesthetics and functionality. I3 described a new, novel feature in his part that his manufacturing vendor wanted him to change in order to make it easier to manufacture:

> *"So that was something that they pushed back really hard on, like, 'We can't do this. We don't want to do this. And here's why it's going to fail.' And then we pushed back and said, 'Here is why it's important to us, and here's how we're going to help you make it work, and here's why we think it's possible.'"*

Five interviewees mentioned that good vendor relationships could result in a smoother development process, reduced cost, and faster resolution of problems, making it a crucial and high-stakes relationship. As I3 described, *"It's like getting married to someone, picking a factory. You have to be 100% sure that you can trust the person, and that you have good communication, and that you're both in it for the long haul. Because it's not going to be easy and the stakes are really high."* The importance of having good relationships with external partners made interpersonal skills valuable for engineers, as well:

> *"It's all about speaking with people, making sure that what you want to do is achievable. Then you have to go in the factory, make sure that everyone understands what you want to do. It's more about relationships than [having] an engineering degree. So I'm pretty sure that someone who is good with relationships doesn't have to do any engineering degree. [...] You learn so much more in the company, that I'm pretty sure if we find someone with a good mind and quick thinking and good relationship with people, he can do [a good job] for sure." (I11)*

Some interviewees described showing rough but mostly complete CAD models to potential manufacturers to receive feedback on their design. This practice was viewed as a way to communicate geometric information quickly while it was still relatively easy to incorporate changes into the CAD model. I11 said he only contacts suppliers when he has engineering drawings of his design because the most useful feedback was provided when suppliers could comment on specific parts and features. But I11 acknowledged that the work going into creating CAD models or drawings could be wasted effort, based on feedback from the manufacturer.

> *"...the more you want to define the part, the more time you spend before having your first feedback. Maybe you're going way too deep in the direction that they cannot achieve[...] So you want to integrate them in the process as early as you can but you don't want to show them a drawing which is not really defined otherwise they will misunderstand."*

Other experts that were consulted include informal advisors, paid design consultants, and peers at other startups. Three interviewees described utilizing outside design consultants when their internal team was small and lacked experience. Interviewees at mature startups described consulting experienced co-workers and supervisors, but this was not always an option for startups with few employees.

3.2.2 Source of DfM knowledge: Learning from experience

Interviewees highlighted learning more from their failures than from their successes. I10 described a mantra his team followed: to "fail fast." Failure was viewed as inevitable, and so by trying out different designs quickly, the development process could move more efficiently. One reason to learn from experience was that *"the manufacturing stuff is so specific to every industry that you really have to just learn it on the job by doing" (I3).* Visiting manufacturing facilities to observe the manufacturing and assembly processes was mentioned by several interviewees as a learning resource. As I9 said, it is valuable: *"... being on site, just going to a factory, visiting how they do things. And then when you actually see an operator do something, then you realize 'Oh this is actually not* *good.' "* Two interviewees described needing to earn manufacturing "scars" to become better at NPD:

> *"To actually get good at it, you have to do it for a long time. And I think maybe that's why in software you see a lot of young hotshot folks building software, and manufacturing is like all crusty old dudes, because it just takes a lot of experience and it takes getting beat the hell up several times. [...] I think that molds you into someone who understands manufacturing and can build a product, but [...] you have a lot of scars to really be good at it." (*I2)

The most useful manufacturing knowledge and skills were gained through participating in NPD. As I12 said:

> *"It's really funny because we really like to blame our suppliers for issues that come up with them building our parts. But when it comes down to it, if we would have designed them better, then they wouldn't have run into issues with them. And so having the experience, and knowing what can go wrong, and the limitations of these processes, goes a really long way in helping to prevent those issues."*

3.2.3 Other sources of DfM knowledge

Interviewees discussed the benefits and limitations of other sources of DfM knowledge, including their formal education, internet resources, software tools, models, and existing designs. Interviewees described many limitations with formal education as a strategy to gain DfM knowledge. I1, when asked what he had learned about manufacturing in his undergraduate education, responded "*absolutely nothing.*" Formal manufacturing education was described as being theoretical and not applied enough to help with designing products for mass manufacture. I12 responded to being asked what he learned in his education about manufacturing with laughter, before noting:

> *"I actually learned very little about it in my education. I think I had really only one course where we reviewed some of the manufacturing processes. And I remember for my capstone project when I was finishing my undergrad, we were doing... a really cool project to redesign how surfboards are manufactured. And I remember having these pie-in-the-sky ideas about things you can do with sheets of plastic that were just completely unreal. Over the course of my education, and that project too, nobody came forward and was just like, 'Yeah those capabilities, those processes, just don't exist. Just because you dreamed all this stuff up doesn't mean you can do it.' "*

Some interviewees mentioned positive aspects of learning about manufacturing in their formal education, such as experiential learning opportunities (e.g., student design-build club teams, factory tours, and case studies). Two interviewees who earned PhDs relating to manufacturing were more positive about their manufacturing education than other interviewees, but they also described their knowledge as high-level and not sufficient for employing DfM in NPD. Four interviewees mentioned using internet resources (e.g., Dragon Innovation's blog and The Bolt Blog) and three interviewees mentioned textbooks for gaining high-level manufacturing knowledge.

Three interviewees described using CAD-based manufacturing simulation tools (e.g., Moldflow to analyze injection molding manufacturability) of their parts, but their usage was limited. Some interviewees specifically stated that they didn't use such tools because of the funding and timing constraints associated with their startups. I11 described not using CAD-based analysis tools because *"You just go quick and and you base everything on your experience just because you don't have so much time" (I11).* Similarly, I3 noted*"I didn't have access to [injection molding simulation software at my startup]. It was too expensive. And I wouldn't have known how to use it anyway…But I kind of did [use it] by extension, just by sending stuff to vendors and getting their feedback"(I3).* Two interviewees described using theoretical predictive cost models developed by universities and national labs to analyze the feasibility of different technical concepts.

3.3 Emergent DfM strategies

After completing our thematic analysis, we synthesized 10 emergent DfM strategies mentioned by interviewees by evaluating the timing with which they were employed and the sources that were utilized. Then, we categorized these strategies based on the levels of abstraction presented by Patterson and Allison (2019). Specifically, we have four levels under which each strategy is categorized*: considering manufacturing processes* based on a fundamental knowledge of different manufacturing processes; *understanding manufacturing constraints* on the use of the process in question for a particular part; *identifying manufacturability constraints* dictated by the process in question on detailed part features; and *troubleshooting manufacturability problems* when manufacturability constraints are not fully addressed during design stages and issues arise during production. The strategies are shown in Fig. 3.

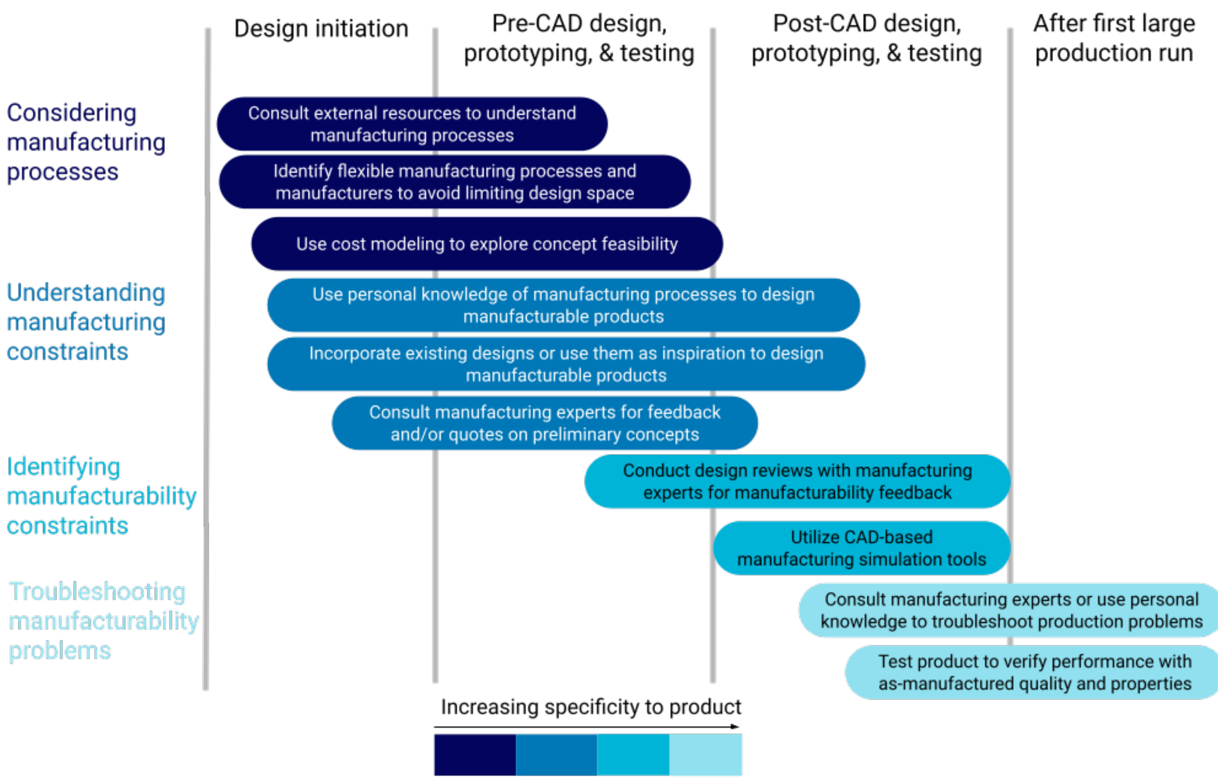

Figure 3. Interviewees described using a number of design strategies related to manufacturing and manufacturability, with varying levels of specificity to the product under development as NPD progressed

The first three strategies were used to understand and leverage manufacturing processes and capabilities: *consulting external resources to understand manufacturing processes* (e.g., touring new manufacturing facilities or reading blogs); *identifying flexible manufacturing processes and manufacturers to avoid limiting the design space* (e.g., choosing additive manufacturing because it allows for more freedom of form); and *using cost modeling to explore concept feasibility* (e.g., using a cost model to compare the cost of different product concepts).

To understand manufacturing constraints, which had a slightly higher level of specificity, interviewees employed several strategies: *using their personal knowledge of manufacturing processes to design manufacturable products* (e.g., relying on knowledge of machining to come up with a concept that would be easy to machine); *incorporate existing designs or use them as inspiration to design manufacturable products*; and *consulting manufacturing experts for feedback and/or quotes on preliminary concepts* (e.g., describing a design to a manufacturer and asking for feedback on feasibility). For identifying manufacturability constraints associated with specific part geometry, we identified two strategies: *conducting design reviews with manufacturing experts for manufacturability feedback* (e.g., reviewing CAD models or drawings with vendors before starting production); and *utilizing CAD-based manufacturing simulation tools* (e.g., using simulation software to predict warpage from injection molding).

Once mass production began, we identified two strategies, which were highly specific to the product being developed: *consulting manufacturing experts or using personal knowledge to troubleshoot production problems*; and *testing the product to verify performance with as-manufactured quality and properties*. Interviewees described only a few problems at this stage. Typically, the manufacturing problems could be addressed with process changes in collaboration with the manufacturer, and only "*10-30% of the time we actually do need to make a change to the design itself*" (I2). Four interviewees mentioned the importance of moving quickly to produce high-fidelity prototypes with the manufacturing processes and materials used in final production. This strategy was mentioned as a way to reduce development times, decreasing the risk of another startup infringing on the designer's startup's market share. I6 summarized this strategy as "*don't fight the prototype*." As I1 described his lesson learned:

> *"One thing for sure would be trying to move faster to higher fidelity prototypes or just directly injection molding things... injection molding these days is so cheap and fast that there's way less of a barrier to doing like prototype injection molds, right? [I would try] to move a lot faster to...we're going to cut the mold, and we know that we're going to need to change the mold, and maybe cut another mold. But I definitely wasted a fair amount of time trying to learn things through 3D prints or hacky prototypes that I just couldn't really learn."*

3.4 Differences in DfM strategies among interviewees

There were some differences in the DfM strategies mentioned by interviewees, depending on the interviewee's experience and perspective and the maturity of their startup. Figure 4 summaries the most commonly described strategies across all interviewees, with counts of the unique experts in which the interviewee described applying or planning to apply the related practice during NPD. This figure illustrates the number of times a strategy was mentioned, but may not reflect the frequency with which each interviewee used each strategy.

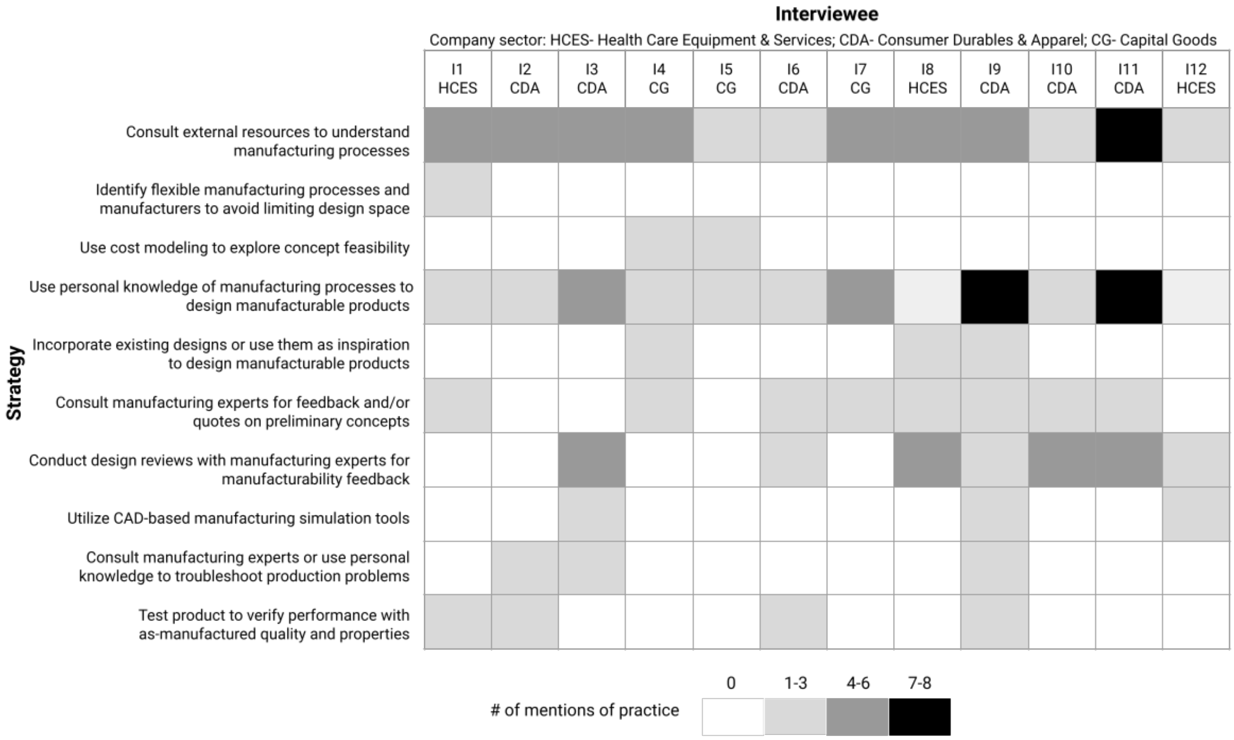

Figure 4. Heatmap showing the most commonly described design strategies related to DfM

Some of the identified DfM practices are only feasible to use once a designer has gained experience. It is difficult to identify flexible manufacturing processes or manufacturers or use personal knowledge or existing designs to guide the design of manufacturable products without prior manufacturing and NPD experience. Cost models and CAD-based software tools require some expertise to use. Most interviewees described using strategies that required less prior knowledge or experience, relying more on manufacturing experts as references to understand manufacturing processes, and to provide feedback on concepts and detailed designs. This dependence on external expertise reflects the lack of practical preparation our interviewees felt from formal education.

The current state of NPD at the interviewees' companies also influenced the strategies that they described most frequently. All three interviewees at startups that had not yet deployed a product focused on DfM considerations at design initiation and pre-CAD. Only one interviewee described reusing existing designs to benefit from the DfM knowledge already captured in existing designs, which is unsurprising given most interviewees worked at startups that were not mature enough to have released several products.

The only two interviewees who described using cost modeling were both working to develop products in the capital goods industry. Their companies' goals were to develop cost-effective, scalable solutions for industry, and so their technical teams focused on scientific research and development more than product development. We did not observe additional differences between interviewees' DfM strategies based on startup characteristics, such as different amounts of funding. DfM activities were described as being driven by individual employees, and no formal company policies to standardized DfM activities were described, so company characteristics did not greatly influence DfM activities.

3.5 Designers' perspectives on DfM

Interviewees described making many manufacturing decisions throughout the design process, from selecting manufacturing processes to conducting quality control. Eleven interviewees described actively communicating with vendors and deciding which vendors would produce components in their final product. Overseeing manufacturing was often described by interviewees as a core job duty. As I3 said, *"The conversations that we have with the manufacturers are kind of the bread and butter of what we do."* I10 said his job did not stop until the first product rolled off the assembly line.

All twelve interviewees emphasized the importance of considering manufacturing constraints and costs at some point in their design process. I11 emphasized the centrality of DfM to his job, saying that when someone brings them an idea for a new component:

> *"...my job is not just to create a CAD and send it to the vendor, it's also to think about the way it's going to be done, and to make it kind of cheap and easy to produce already. Because if you just send the CAD from the [industrial] designer, you're not useful, you're just sending emails. And my job is really to think about the way it's going to be done. Think about the clever way to do it. Make it easier and cheaper."*

DfM was viewed as one of the interviewees' main contributions to their companies, and robustly thinking about DfM set them apart from other engineers. As I8 said, *"The engineering and the design for manufacturing [on our product] is so radically different [since I joined the team]. It's awesome. I'm very proud of it."* Four interviewees described observing other engineers, sometimes within their own company, who did not consider manufacturing constraints and then had poor outcomes. I10 described seeing "*battles*" in his office around design decisions made by a seasoned engineer with 20 years of experience who was brought in on a temporary assignment:

> "*... [the engineer] designs the [component] on his own and then throws the [component] over the fence to the manufacturer, then tells them to make it.[...] At this point, you're too far along to change because you have a timeline, everything is dialed from your point of view, and the manufacturer doesn't want to do it and has a list of things to change because it just doesn't work for him, for his process."*

Interviewees emphasized learning to perform DfM early in NPD to ensure smooth production later. I10 described designing products with feedback from the manufacturer:

> *"It's time you invest upfront. It's meetings, its arguments, it's a lot of time. But down the road, when you have your product manufacturing, testing samples, assembly...that goes silky smooth. That's where it pays off for sure."*

Most interviewees expressed pride in doing good DfM, but a few interviewees made it clear that no amount of DfM could completely prevent manufacturing problems, especially for radically new designs and technologies. One interviewee with approximately 6 years of experience said, *"the manufacturing issues are an inevitability [....] They're always going to crop up"* (I2).

3.5.1 Learning to value DfM

The value of DfM was often learned through trial-and-error, where an interviewee tried to design something without considering manufacturing constraints and then experienced poor outcomes. Interviewees talked about starting their job with little relevant experience or knowledge about manufacturing, feeling ill-prepared from their formal education. Two interviewees described having wasted time designing components that could be bought off the shelf early in their careers, learning their mistake when they showed their designs to more experienced colleagues. These hard-earned insights seemed to stick with interviewees in a way that formal learning did not.

3.5.2 Downside of considering DfM: limiting creativity

Three interviewees mentioned a potential downside of early DfM: the challenge of balancing creativity with practical considerations (e.g., cost and manufacturability) at an early concept development stage to avoid constraining their idea generation. I12 described benefits and drawbacks of considering manufacturability early in the concept generation process:

> *"[Considering manufacturability] in some ways, it limits your thinking, because you know what is actually possible, but in some ways it actually expands [your thinking] because it's like 'Ok, well they can do this,' and that'll spark other ideas that you can potentially do with that stuff."*

I1 talked about spending too much time focusing on manufacturability early in the development of his startup's product when he should have focused on user needs:

> *"I think I'm less concerned about manufacturability than I was at the start... I put all this effort into designing them so they could be really easily machined and really easily molded. And then later on, [I] ended up learning a lot of that stuff didn't matter as much. [...] The quantities are so small that it just wasn't a big deal, or my time would have been better spent elsewhere. Then the next phase has been more thinking about trying not to get stuck in the problem of just getting this one, nitty gritty technical problem solved, but stepping back and really trying to think, 'Does this problem even need to be solved? Does this actually make the device better for the user?' "*

This theme was repeated in descriptions of interviewees leveraging the knowledge they had gained from experience. While gaining experience was seen as the primary way to gain DfM knowledge, it could also impact creativity. As I3 stated, *"I think this is why there's so many young people that make so many really cool innovations because it's only young, inexperienced people who are audacious enough to think that they can do something differently."*

4. Discussion

4.1 Limitations

There are several limitations of this study. First, the interviews we conducted were retrospective in nature, asking interviewees to recall a project they had previously worked on, and therefore may be subject to biases or errors in interviewees' memories. Second, we did not tie our findings to the outcomes of interviewees' projects. Therefore, in this paper, we are not able to describe how DfM considerations (including timing, extent, and use of strategies) may have affected NPD outcomes. However, the results of this paper serve to describe the current ways practitioners apply DfM considerations, which therefore sets the stage for future studies to explore the impact of applying these DfM considerations in NPD and to build theory (e.g., through a more longitudinal grounded theory approach) on how DfM considerations early in NPD may manifest in notable design changes prior to implementation. Third, we focused on the individual perspectives of interviewees and not on the perspectives of their companies. Consequently, our study focuses on individuals' experiences in considering DfM in the NPD process, but does not explore the impact of the systems surrounding individuals as they work on DfM and NPD. A future study could examine how company-wide systems at startups consider manufacturing during the design process.

4.2 Shared set of DfM strategies used by interviewees

We found that the engineers at startups that we interviewed shared a small common set of DfM strategies they applied in their NPD work (Figure 3 and 4). The most commonly used strategies relied on experts as a source of manufacturing and manufacturability knowledge. Manufacturers were a vital source of knowledge and feedback to support decision-making. Relying on manufacturers to help improve their designs was seen as an efficient strategy because it did not require interviewees to gain experience through trial-and-error, a lengthy and expensive process. CAD-based simulation tools, DfM heuristics and guidelines, and other formal methods were not frequently used. Below, we discuss the implications of the common DfM strategies used by interviewees in further detail.

4.2.1 Importance of relationship with manufacturers

Interviewees all agreed on the importance of fostering a productive working relationship with manufacturers as critical to their DfM process, echoing prior work linking supplier involvement to successful NPD and product performance (Johnsen 2009; Marion et al. 2015). 4 of the 10 DfM strategies we identified relied at least partially on manufacturers, who could provide industry-specific and product-specific feedback to novice engineers. Interviewees used manufacturers as a source to gain general manufacturing and design knowledge, similar to how engineers at established companies use experienced colleagues (Deken et al. 2012). Interviewees worked to maintain good relationships with vendors. I11 summarizes a prevailing sentiment among interviewees in this study on the importance of hands-on work and relationship-building:

> *"And it's all about speaking with people, making sure that what you want to do is achievable, then you have to go in the factory [and] make sure that everyone understands what you want to do. It's more about relationships than an engineering degree."*

While the relationships between vendors and interviewees were generally fruitful and beneficial, these relationships can be challenging to manage. Marion, Eddleston, Friar, & Deeds (2015) discovered that "socioemotional bonds [like those between design engineers and vendors] clouded the entrepreneur's judgment of the partner's abilities and led to problems that threatened the venture's survival." Some anecdotes that indicated socioemotional bonds were developed by interviewees: I2 reported feeling conflicted when deciding to change vendors, ultimately flying out to visit the current vendor in person to "*[fire] them in a nice way*" and I3 described picking a factory as similar to getting married. Because the engineers we interviewed relied on external vendors to support design decisions from initiation through mass manufacturing, this relationship is crucial for successful DfM. Future work should identify best practices to support startups in incorporating manufacturers into the design process while minimizing potential risks and biases. Engineers at startups should be aware of the potential risks associated with close partnerships with one manufacturer, and should consider soliciting feedback from multiple partners early in the design process.

4.2.2 Using personal experience to guide design

The second-most commonly discussed strategy we identified was relying on personal knowledge of manufacturing processes to design manufacturable products. As engineers gained experience with NPD, they were better able to identify manufacturing constraints and capabilities, and use that knowledge to improve their designs. The experience of learning about their products and manufacturing processes by trial-and-error was discussed positively. I10 described the value of failing fast to explore risky ideas during the development phase, learning more about their design when prototypes failed or gave unexpected results. Trial-and-error is valued in the design industry as a way to explore creative ideas iteratively (e.g., global design firm IDEO's adage of *"fail faster to succeed sooner"* [Brown 2013]).

While relying on trial-and-error was reported as an effective *learning* strategy for interviewees, literature indicates that it is not always an effective *business* strategy. In a study of 58 startups, trial-and-error learning was not the most effective management strategy for projects with high uncertainty and high complexity (Sommer et al. 2009). Similarly, Freeman & Engel observe that trial-and-error learning is more likely to lead to fatal mistakes at startups with rapid growth (2007). Formal education should help engineers gain applied experience and knowledge *before* entering the workforce, enabling them to use personal knowledge to design manufacturable products without having to fail in the high-stakes NPD environment. Graduating with more knowledge of manufacturing would allow engineers to use more of the strategies we observed (which often required some expertise or experience to employ) rather than solely relying on experts.

Interviewees noted that their engineering coursework was helpful for learning theory and identifying resources to use later in industry, but felt their education was not directly or sufficiently helpful because of insufficient focus on applications and a lack of guidance for mass manufacturing. Based on our interviewees' experience and prior literature (e.g., Eggert 2006; Mirkouei et al. 2016), more applied and industry-driven content (e.g., DfM projects, industry case studies of unsuccessful/insufficient applications of DfM, hands-on manufacturing training, and industry field trips) are needed in undergraduate manufacturing education. Curriculum updates should focus on providing students with opportunities to employ more DfM strategies, especially complex or expertise-dependent strategies and tools such as CAD-based DfM software and cost models. We found limited use of such tools, in part due to constrained resources, but also due to lack of familiarity and expertise.

4.2.3 Introducing engineers to additional DfM strategies

The interviewees in this study did not apply many formal DfM methods in their work, and instead relied heavily on expert feedback and prior experience. Our study echoes the findings of Gericke, Kramer, and Roschuni (2016), who found that engineers and designers consider their network of professional and personal contacts to be their most important source of new design methods, above books, literature, or online. Similarly, Eckert et al. (2005) found that experienced designers may rely on tried-and-true design strategies learned through prior experiences, limiting the creativity they bring into their designs. The interviewees in this study made limited use of the internet in finding new DfM methods, which may suggest their challenges in finding appropriate DfM methods.

Gericke et al. (2020) suggest that the design research community can better support practitioners in industry by moving away from developing "isolated" design methods and moving towards developing "method ecosystems". Such ecosystems would include sets of robust and validated design methods that operate in synergy and are able to be flexibly adapted and applied by industry practitioners. Further research is needed to explore how an ecosystem of DfM methods can improve NPD outcomes in startups, and if so, how to introduce an ecosystem of DfM methods to engineers and designers working at startups. Method ecosystems to support creative but feasible design (such as our identified emergent strategy to identify flexible manufacturing processes and manufacturers to avoid limiting design space) may be particularly impactful given interviewees' described focus on early DfM and the lack of DfM tools compatible with this phase of the design process. Researchers developing new DfM tools should also consider cost, as startup engineers are more likely to utilize free resources given their constrained resources.

4.3 Individual and company perspectives of DfM during NPD

In general, interviewees shared relatively uniform perspectives on the importance of DfM during NPD. Interviewees learned the value of DfM from prior experience, particularly from negative experiences associated with failures to consider DfM in the past. The individual commitment to DfM our interviewees reported may be related to their strong attachments to the products they develop, a characteristic of inventors at startups (Freeman and Engel 2007). Additionally, interviewees gained awareness of the importance of manufacturing in NPD through personal experience. The feeling of "earning their scars" through prior experience was salient for interviewees, and this feeling may contribute to interviewees feeling committed to considering DfM in NPD. Manufacturing and design seemed intrinsically linked for our interviewees, in part because they were typically responsible for both design and manufacturing decisions. Perhaps because their knowledge about DfM was personal and experiential, interviewees presented DfM as an individual value.

This value was not necessarily reflected in their co-workers or their company as a whole, given the lack of established DfM or NPD processes we observed. Approximately half of interviewees mentioned dealing with a lack of structured feedback or collaboration. Interviewees described having few to no formal processes for design reviews, problem escalation, or collaboration with multiple engineers on a design. This finding is supported by prior work indicating that the NPD process at startups and other small companies is less formal than at more established companies (Skalak et al. 1997; Davila et al. 2010; Marion et al. 2012) and that management at small companies may not see the importance of a formal product design process (Millward and Lewis 2005). Startups have a small number of employees who have direct ownership of a product's development, so the implementation of DfM is often at the discretion of a few employees. As they grow, startups should consider institutionalizing some of the emergent strategies we observed (e.g., appointing an experienced engineer as a DfM champion to conduct design reviews, offering training to expose inexperienced engineers to commonly used manufacturing processes in their particular industry, and providing guidance on the frequency and timing of asking manufacturers for design feedback).

4.4 Challenges applying DfM in early idea generation and development

In general, we noted a tension between applying DfM early in the design process and remaining creative in making early design decisions. Many NPD texts (e.g., Ullman 2016; Ulrich et al. 2020) say that manufacturing constraints and costs should be considered throughout the development process to ensure economical designs. However, three interviewees mentioned feeling that manufacturing experience makes one less creative, echoing prior work which has observed a tension between creativity and the practicalities of commercialization (Swink 1999; Freeman and Engel 2007; Johnsen 2009). At startups, a single individual may be responsible for design decisions, so this tension between creativity and feasibility may feel more personal. Because design fixation due to familiarity with a particular manufacturing process has been observed in prior work (Abdelall et al. 2018), the expertise (and potential fixation) of a single designer can dramatically impact the design process and, ultimately, product performance. Engineers employed at startups should be aware of the potential for design fixation associated with prior design and manufacturing experiences and work to balance feasibility with creativity.

We observed that interviewees who worked at large infrastructure-focused startups (I4 and I5) were unique in that they spent time early in the design process on high-level planning and conceptual assessment of manufacturability, while engineers at startups creating a smaller product mostly began applying DfM after creating a CAD model. However, NPD guides (e.g., Ulrich et al. 2020) cite early and iterative cost modeling as a fundamental strategy in DfM. More research is needed to understand the balance between early considerations of manufacturing constraints and creativity in ideation and to develop methods to support creative and manufacturable designs.

5. Conclusion

In this study, we employed a qualitative approach to illustrate engineers' DfM attitudes and strategies at startups. Interviewees did not feel their engineering education sufficiently prepared them to design products for mass manufacture. The value of DfM was learned through negative personal NPD experiences when DfM was not emphasized, with several interviewees describing this process as "earning scars." We identified 10 emergent DfM strategies utilized by engineers at startups, employed throughout the engineering design process. In early stages, the most commonly described strategies to understand specific manufacturing processes and constraints, chiefly by relying on manufacturers for expert advice. Later in the design process, interviewees shared CAD files with manufacturers to solicit detailed manufacturability feedback on part features. Cost modeling and CAD-based manufacturing simulations software were not commonly used.

This research brings new insight into NPD strategies at startups, highlighting the informal nature of DfM in NPD, with personal experience and external experts guiding design and manufacturing decisions. We highlighted common DfM strategies which engineers at startups can utilize and recommended opportunities to formalize and improve DfM practices at startups. The findings of this study can guide future research on how DfM strategies impact startup success to enable engineers and entrepreneurs to navigate NPD more efficiently, driving innovation and economic growth.

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