Making Hardware Devices at Scale is Still Hard: Challenges and Opportunities for the HCI Community.

Bo Kang*
University of Cambridge
Cambridge, United Kingdom
bokang1@meta.com

Steve Hodges
Lancaster University
Lancaster, United Kingdom
steve.hodges@lancaster.ac.uk

Per Ola Kristensson
University of Cambridge
Cambridge, United Kingdom
pok21@cam.ac.uk

Abstract

Embedded systems and interactive devices form an essential interface between the physical and digital world and are understandably an important focus for the HCI research community. However, scaling an interactive prototype of a new device concept to enable effective evaluation or to support the transition to a production-ready device is incredibly challenging. To better understand the issues innovators face when scaling up interactive device prototypes we report the results from 22 interviews with practitioners in the interactive device field, including eight academics involved in the HCI and manufacturing research communities. In our two-phase analysis we identify and validate the following four recurring themes. First and foremost is the observation that "creating relationships with industry" is hard. Second, "effective communication requires a lot of effort" despite the availability of modern collaboration tools. Thirdly, we observed that "understanding the manufacturer's perspective" can be difficult. Finally, "prototyping is nothing like production"—the vast difference between these two activities still surprises many. Additionally, our university-based participants gave us further insights and helped us to identify challenges specific to the academic context, pointing to a number of opportunities relating to hardware device scaling.

CCS Concepts

• **Hardware** → **Design for manufacturability**; • **Applied computing** → **Industry and manufacturing**.

Keywords

interactive device, production, engineering experience

ACM Reference Format:
Bo Kang, Steve Hodges, and Per Ola Kristensson. 2025. Making Hardware Devices at Scale is Still Hard: Challenges and Opportunities for the HCI Community.. In *CHI Conference on Human Factors in Computing Systems (CHI '25), April 26–May 01, 2025, Yokohama, Japan.* ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3706598.3713214

1 Introduction

The billions of embedded systems and interactive devices that form an essential interface between the physical and digital world are understandably an important focus for the HCI research community. However, scaling the prototype of a new concept in this area to a production-ready device that can be manufactured reliably and cost-effectively is incredibly challenging. There are, of course, mechanisms that newcomers can leverage to learn about this complexity, and the potential pitfalls when navigating this transition from prototype to product. But there are also many well-documented examples of failure! Put another way, whatever information and materials exist to mitigate these problems, it is often not sufficient.

We observe that this state of affairs has two different implications for the community of researchers who develop new device concepts, and we explore the user values and experiences that can result. First, the likelihood of a promising device concept graduating from a research lab by making the transition from prototype to product is low, simply by virtue of the fact that a notable fraction of efforts in this regard currently fail. Second, and perhaps more subtly, many of the problems that cause difficulty when scaling to a commercially-viable device also present a problem for scaling while still at the research stage. For example, researchers using a novel device for a wearable scenario or a distributed sensing application may require hundreds or thousands of devices to validate their research—causing them to bump up against the same issues.

In an attempt to understand more about the challenges of making devices at scale, researchers have studied and analyzed successes and failures. A key factor appears to be the sheer number and variety of disciplines needed to successfully produce a modern hardware product. In addition to the intellectual challenge, this typically also necessitates the coordination of a number of suppliers and manufacturing partners. In one particularly relevant study, Khurana and Hodges presented an analysis of interviews with 25 individuals with experience taking hardware devices into low volume production [24]. They observed four main categories of problems: (1) gaps in technical knowledge; (2) gaps in non-technical knowledge; (3) a general lack of rigor; and (4) the aforementioned importance of a network of partners.

In this paper we aim to build on the findings of [24] in two main ways, mirroring the two implications for device-related research that we described above. More specifically:

(1) We drill down in particular on the importance of partnerships by asking a new set of 14 practitioners from industry, including some manufacturers in addition to product creators, questions to elicit their experiences working in collaboration. From this we identify and present four themes that recur across our interviews.
(2) We presented these four themes to 8 additional participants, this time experienced academics, with the aim of understanding the relevance to the HCI research community. We report

*Also with Meta Reality Labs.

CHI '25, Yokohama, Japan

ACM ISBN 979-8-4007-1394-1/25/04
https://doi.org/10.1145/3706598.3713214

on their own experiences, their observations and reflections, and opportunities for the HCI community that surfaced in these discussions.

In the next section we examine some of the extensive body of prior work relevant to the topic of embedded and interactive device development. Following that, we describe the two-phase study that forms the core of this paper. After analyzing the transcripts from our interviews, we reflect that despite the availability of more formal support through textbooks coupled with anecdotal evidence including many 'war stories' that cover productization, inexperienced creators still generally underestimate the transitional complexities of moving from prototyping to production. We note that quality and frequency of communication, which remains critical to success, is influenced by information asymmetry between creators and manufacturers.

We hope that exposing the HCI community to the issues intrinsic to hardware scaling will (1) clarify and delineate the problem space; (2) help the current and future hardware practitioners among us to identify and address the associated challenges; and (3) ultimately inspire a broader community to devise new tools and approaches to mitigate the transitional challenges and improve the overall experience of scaling hardware research for more impact.

2 Previous Work Related to Hardware Development

2.1 The Value and Nature of Device Prototyping in HCI

The HCI field has long been interested in embedded systems and interactive devices, as they continue to weave themselves into our daily lives. Device prototypes deliver functional manifestations of ideas and support the evaluation of how effectively they work both from a functional perspective and from a usability point of view. Within the field of HCI, a "prototype" is more of a proof-of-concept than the kind of fully-functioning model that the term is frequently understood to stand for among device manufacturing companies. Whatever tools and methods are adopted, the prototyping stage is intended to create a shared vision or common ground. In this sense, many details that are pertinent to the production of a device need not be addressed by a prototype.

Although you might assume that a hardware prototype of an interactive device is a point on a trajectory towards a fully-realized commercial product [30], in practice these prototypes are optimized for the evaluation of a theoretical concept, or the potential of a new device and the associated user experience, and are often physical manifestations of the prototyping journey rather than representations of the product that might follow [20].

On the other hand, the focus of many designers has shifted from designing objects to designing socio-material assemblies, as mentioned by Bjögvinsson et al. [4]. This stresses the challenges in looking beyond the immediate technical design challenges for a given product, and towards a process that involves future stakeholders as co-designers. Hence, Odom et al. [30] proposed the creation of *research products* as an extension of *research prototypes* to support a more in-depth evaluation of new device concepts than what is supported by a typical HCI research prototype.

The terms *research prototype* and *research product* cover a considerable span of studies and evaluations conducted within the HCI field. However, the HCI community has largely overlooked the gap between both of these and fully-fledged products. A central contribution in this paper is to raise awareness and understanding of this gap among hardware prototype designers and researchers in the HCI community, and to illustrate the consequences of this gap on the success of translating an HCI hardware prototype into a product.

2.2 Tools and Materials that Support Device Development

The development and deployment of device prototypes has been a growing practice in research, supported by a variety of personal and small-batch production tools and techniques that are constantly evolving [14, 15, 28]. The sudden emergence of a breakthrough component or software can drive a major product into technology obsolescence before it sees the light of day [7]. This kind of technological uncertainty can disrupt the design and production schedule, promoting device creators to choose small-batch production as an effective way to mitigate risk. HCI researchers have also been actively exploring processing methods that can be potentially implemented in manufacturing, such as 3D printing custom optical elements for devices containing optoelectronic components [43], using spray coating as an innovative fabrication method to create an interactive display of arbitrary shapes [17], and reconfigurable tactile elements enabling dynamic physical controls on wearable devices [36]. However, while the techniques proposed are interesting, they may not be suitably refined and practical to merit adoption for actual production.

Although prototyping and production are both critical parts that constitute the development of products, these two stages are intrinsically different in terms of participants, methods, focuses, emphases and goals, see Figure 1. While prototyping is about exploring ideas and options, the focus of the transition from prototyping to production should be removing uncertainties. The many tools and platforms that exist to support prototyping are less useful and may even be counter-productive when scaling a hardware device.

There is a lot of material guiding people through the prototype-to-production process, in which the transition stage is variously called 'adaptation' [6], 'preparation' [3, 32], 'productization' [12, 22, 44], 'design for manufacturing' [11, 33, 39, 42], 'design for production' [18] and 'pilot production' [26]. However, these concepts have not been strictly defined—they have overlaps with each other and are often used interchangeably. Indeed, many of them include elements of both prototyping—creatively capturing design concepts and testing with users—and production—rigidly transforming materials into finished units through the use of labor, machinery, and tools. In reality, smooth transitions from prototyping to production are rare, as are studies that have been conducted to help researchers understand, analyze, and improve the working environments and relevant experience of creators who are tasked with going through this process.

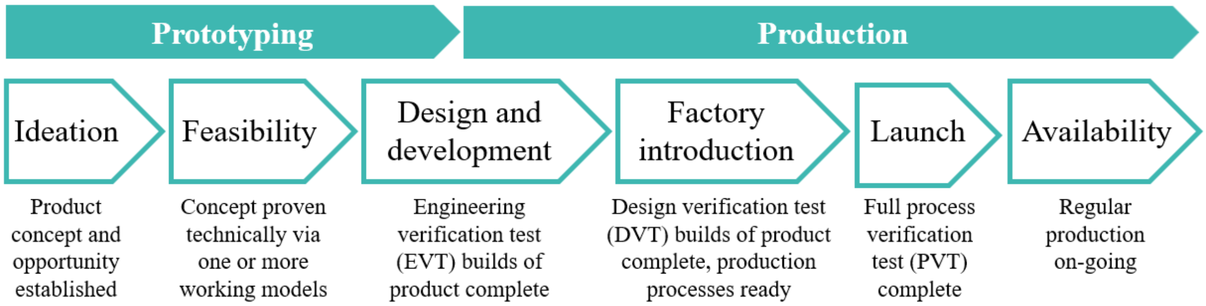

Figure 1: The many activities involved in moving from prototyping to production, as illustrated in Khurana and Hodges [24] (reproduced with permission). Those who do not have first-hand experience of production frequently underestimate how numerous and how complex the activities are.

2.3 Insights from Commercial Device Development

The key steps in the commercial development of an embeded or interactive device are depcited in Figure 1 (taken from [24]). Occasional case studies of individual projects, such as [9], can be insightful for understanding where things can go wrong during this process. As mentioned earlier, one particularly relevant study [24] presented an analysis of interviews with 25 individuals with experience taking hardware devices into low volume production. Jensen et al. [23] extracted information about projects on the Kickstarter crowd-funding platform and used the updates provided by creators as their projects progressed through the manufacturing phase to determine how often products were successfully delivered as planned. Their analysis, based on qualitatively coding these updates, showed that from 114 funded 'Technology' projects on Kickstarter only 61% successfully delivered, and out of these 48% arrived late. Even those that were delivered on time were missing planned features 14% of the time. Tran et al. [40] presented a model predicting if a project would be delayed that was trained on various project features, such as the complexity of the rewards. Kim et al. [25] developed a similar predictive model but also considered the updates and comments to determine if a project would be delayed. These models can provide insights into some causes of delays, including the number and complexity of rewards [40], the number of backers, and the creator experience [25]. However, this work did not investigate factors relating to the transition from prototype to product, or the nature of the partnerships and professional networks necessary for success. Related, Tuo et al. [41] analyzed 440 randomly-sampled projects from Kickstarter to determine how delivery performance was affected by issues relating to project status, lead time, sourcing and production.

In order to understand the underlying challenges, Hansen et al. [2] used a mixed methods approach to study prototyping in product development processes in industry with eight practitioners. Doussard et al. [10] studied the strategies employed by creators without the infrastructure of a 'manufacturing firm' by interviewing 137 makers and evaluating their approach for accessing capital and production networks. Similarly, Li et al. [27] surveyed 3,139 global makers to examine regulatory, normative, and cultural elements impacting the transition of hobbyists to entrepreneurs.

2.4 Insights Relating to Remote Collaboration

In recent years a global shift toward hybrid working has inspired researchers to revisit the role of interaction and communication technologies in supporting effective distributed working [34]. In a survey of 209,000 people in 190 countries by Boston Consulting Group and The Network [16], 89% of respondents admitted that they expected jobs that allow them to work remotely, having tasted remote work during the pandemic.

Different sectors of the workforce have different experiences moving to hybrid and remote work; information workers with established careers found it the easiest, whereas frontline workers found it much harder [21]. It has also been easier for distributed teams in business and sales roles to establish a working practice that integrates remote and hybrid meetings [37], compared with "solo workers", who find collaboration more challenging when conducted remotely [21]. A quantitative survey reveals that 30% of respondents found the collaborative generation of new ideas challenging when remote [35]. Planning (17%), sharing information (17%), and solving problems (16%) were also reported to be problematic. Specifically, people reported difficulties conducting technical discussions that involve the use of devices and physical ecosystems [21].

We mention all this because of the importance of effective collaboration on the outcome of the commercial collaborations that are essential when scaling a hardware device from prototype to product. We are interested to know whether, given the recent uptick in the use of remote collaboration and hybrid working tools and attitudes, these commercial relationships and the technical device developments they are working towards have become easier to manage remotely. We image there are a plethora of research opportunities to be unearthed to improve the experience of device creators in the context of hybrid working for hardware scaling.

3 Learning from Practitioners

Despite the large amount of literature about manufacturing and production, it's clear that many practitioners—especially those who are relatively inexperienced with scaling hardware—often make mistakes that would seem to be avoidable. As previously alluded, Khurana and Hodges [24] categorize the challenges into four topics: (1) gaps in technical knowledge; (2) gaps in non-technical knowledge; (3) minimum viable rigor; and (4) building relationships and a professional network. We wanted to drill down further into these topics in order to better understand specific issues, and decided to carry out our own interviews with practitioners to learn more.

3.1 Study Objectives and Approach

While a broad-ranging study asking practitioners about specific issues they had faced (both technical and non-technical) would undoubtedly result in some interesting conversations, we felt that a more focused approach might help to highlight recurring systematic issues. We decided to focus on the last of the issues listed above, namely the importance of professional relationships. Our intuition was that communication with partners and other stakeholders would be part of this relationship building, so we wanted to understand more about that in particular.

We also wanted to better understand the relationship—if any—between the issues faced by practitioners undertaking commercial endeavors to scale embedded and interactive hardware devices, versus practitioners more firmly rooted in the HCI research community. We hoped to determine what issues were common across these two groups and whether these issues are generally waning over time or not.

We designed a two-phase study consisting of semi-structured interviews with three different groups of stakeholders. In the first phase, we interviewed interactive device creators and device manufacturers from industry to understand the challenges facing practitioners as they transition from prototype to product. We aimed to identify their perception of the entire prototype-to-product process, their struggles in particular projects, and their suggestions to smooth the transition, as well as any ideas they had that may inform future efforts to build solutions to address these challenges.

In the second phase, we discussed the themes generated in the first phase with academics with involvement in the HCI or manufacturing communities, and collected their reflections. The academic participants were also encouraged to share their personal experiences, observations, and opinions on the historical development of this area to help us better identify the gaps and opportunities for hardware scaling in the HCI community.

Since interviewees were located in different countries, the two pilots we ran and all subsequent interviews were conducted online with audio recording. Informed consent was obtained from all participants. All participants were interviewed separately, and the interview was conducted by either one or two of the authors. Phase 1 of our study took place in 2021 and Phase 2 in 2022. Note that interviews with the Chinese participants were mostly carried out in Mandarin due to participant preference, and in that case only one author was able to participate.

3.2 Phase 1: Creators and Manufacturers

We used opportunity sampling to recruit five participants and found the others through referrals from these initial participants. The inclusion criterion we specified for referrals was that participants should have experience in taking a new embedded and/or interactive device from prototype to product. We used the maximal variation principle [31] to select participants from the list of referrals we received, aiming to create a diverse panel with a wide range of experiences. As part of this, we included participants with expertise in different disciplines, such as engineering, design, research (who we collectively refer to as 'creators' hereafter), and expertise in manufacturing. We also tried to find participants with different levels of experience. In total we interviewed a total of 14 participants, see Table 1 for details.

Our creators saw themselves as professionals in the area of new product innovation (NPI). Many had previously worked in academia or for established companies and were now part of an entrepreneurial team. They had experience developing products, such as cameras, drones, robots and home appliances. In addition to creators driving the development of new products, and unlike previous studies [24], we also recruited four manufacturers for our interview panel. We define manufacturers as individuals working in companies who operate the machinery involved in device production rather than designing or marketing embedded and interactive devices themselves.

In our Phase 1 interviews, creators were asked to describe their background and professional experience. They were then encouraged to share their perceptions of prototype-to-product processes, the successes and failures while transitioning new concepts into products, and to provide as much insight as they could into issues, solutions, and expectations during the process. A further list of more specific questions (see Table 3 in the Appendix) rounded out the semi-structured interview, in order to initiate further discussion of topics relating to the transition from prototype to product. We were particularly interested in understanding the importance of partnerships, a topic previously highlighted in the literature [24]. These sessions with creators ran from 40 to 90 minutes, with approximately 60 minutes being typical. Interviews with manufacturers followed a similar protocol, although our pilot revealed a recurring issue that they were not as engaged or forthcoming about issues as many of our creators, so we often asked more specific questions based on topics previously raised by creators. As a result, the four sessions with the manufacturers were also shorter, ranging from 20 to 40 minutes.

The Phase 1 interview recordings were machine-transcribed and analyzed using the inductive analysis approach [38]. Interviews conducted in Mandarin were analyzed in Mandarin so that nuances were not lost in translation. We then grouped similar experiences and labeled these emerging categories in Engligh. The ideas that emerged included "communication and presentation issues", "the need for in-person visits", and "tensions between creators and manufacturers". We then conducted several rounds of open coding on the transcripts until the dataset had been fully coded and analyzed. We grouped similar codes together to form higher-level categories, which were discussed among all three authors and refined to reflect repeated patterns.

3.3 Phase 2: Academics

Having learned first-hand from industry practitioners about recurring challenges when scaling hardware, we wanted to understand the academic perspective and especially that of those in the HCI community who create embedded and interactive device concepts. As described in Section 3.1, we formed a panel of academics to whom we posed two questions on two topics. First, we wanted

Table 1: Overview of Phase 1 interviewees

ID	Gender	Location	Education	Occupation	Years of experience in industry
C1	M	China	Bachelor's	Mechanical Engineer	7 years in robots, ranging from education robots to industrial robots
C2	M	China	Master's	Chip Designer	8 years in semiconductor industry and 3 years in running a maker space
C3	M	China	Bachelor's	Industrial Designer	8 years in cellphone design and 2 years in running a design consultancy
C4	M	China	Doctorate	Robotics Engineer	5 years in robotic surgical systems
C5	M	UK	Doctorate	Design Researcher	4 years in inclusive design
C6	F	UK	Master's	Electronics Engineer	3 years in sensor design for home appliances
C7	F	Netherlands	Master's	Design Engineer	5 years in structural design for home appliances
C8	M	China	Master's	Mechanical Engineer	3 years in battery design for drones
C9	F	Singapore	Master's	Electronics Engineer	1 year in electronic module design for consumer electronics
C10	M	China	Master's	Software Engineer	3 years in system development for surface mounter
M11	M	China	Associate	Owner	12 years in original equipment manufacturer (OEM) electronics
M12	M	China	Associate	Engineer	8 years in OEM electronics
M13	M	China	Associate	Engineer	5 years in OEM electronics
M14	M	China	High School	Technician	2 years in OEM electronics

a 'reality check' on our findings—are these issues *really* important in today's environment? Is there anything obviously missing? Second, we sought to understand what relevance all this has to device-based research in HCI. Do these topics occur in academic contexts too, and, if so, is there a benefit in trying to overcome them in an academic context?

We used convenience sampling to recruit eight established academics from universities in Europe, North America, and Australia for the second phase of our study. The inclusion criteria were similar to that in the first phase, interviewees needed relevant research or industry experience in embedded systems and interactive devices, and we prioritized those with an interest in HCI and a track record of publication at ACM SIGCHI venues. R21 and R22 were exceptions in regard to the latter criterion, as they were academics from the manufacturing community. See Table 2 for more details.

The experience of our panel of eight academics varied significantly and included wearable devices, new displays, home appliances, distributed sensing solutions, and physical computing devices. Many of these projects grew out of doctoral research that was subsequently commercialized, while others were inspired by collaborative projects. The users of the resulting hardware products range from from a few hundreds to tens of millions. All of our interviewees had outsourced the production to local or overseas manufacturers after some initial in-house manual work, normally completed by themselves and their collaborators (including masters and PhD students).

In Phase 2 we followed a similar interview protocol; academics were asked to share their background and any relevant experiences with scaling hardware. Next we presented the four high-level themes that emerged from Phase 1, recounting some of the lower level anecdotes which underpinned them. We then asked the academic participants to reflect on these themes—encouraging them to think about whether or not they had experienced similar pitfalls. This semi-structured interview process is described in more detail in Table 4 in the Appendix. Each session in Phase 2 lasted for approximately 60 minutes (ranging from 40 to 75 minutes). A similar process was adopted for data analysis as with Phase 1, whereby new ideas were labeled (by the first and second authors) and when coding was complete these were combined into an additional set of themes that complemented those generated in Phase 1.

4 FINDINGS

In this section we present the key findings from our interviews, split into four main areas that emerged from our analysis. These themes, which emerged during Phase 1 of our research, were also very apparent during Phase 2 and so the discussion in this section spans both phases. We want to flag up-front that readers may, like us, think that many of the issues we report on—and indeed, the high level themes they are grouped into—are somewhat 'obvious' truisms. But as we reflected on this ourselves, we realized that they were 'obviously not' to our participants, at least at the time they were experienced. So in a way what is interesting is that even these basic issues are somehow not sufficiently apparent or suitably addressed, at least for practitioners like those we interviewed, and likely many others [19, 23, 24, 41]. We opted for simplicity in the themes because we felt it reflected the underlying message and would at the same time resonate with a wider audience, including those less familiar with hardware development. We present more context via a series of subtitles to provide additional context and specificity.

Table 2: Overview of Phase 2 interviewees

ID	Gender	Location	Education	Occupation	Years of experience in industry
R15	M	Germany	Doctorate	Academic	23 years in wearables, ubiquitous computing, activity recognition, wireless sensor networks, machine learning and signal processing
R16	M	UK	Doctorate	Academic	27 years in systems and networking for mobile, embedded and ubiquitous computing
R17	M	UK	Doctorate	Academic	25 years in AI and machine learning applied to physical sensing systems
R18	M	Australia	Doctorate	Academic	30 years in novel sensing platforms, interaction, human centred design and digital civics
R19	F	US	Doctorate	Academic	21 years in the intersection of computer science, art, design, and education
R20	M	Germany	Doctorate	Academic	27 years in AI, computer graphics, mobile and ubiquitous computing
R21	F	US	Doctorate	Academic	33 years in product development, manufacturing and quality systems
R22	M	UK	Doctorate	Academic	17 years in VR/AR, vision-based activity recognition, and operator-assistance systems

4.1 Theme 1: Creating Relationships with Industry is Hard

A steep learning curve: In our interviews, creators explained how they felt they needed to appear knowledgeable, professional, and disciplined from the very beginning of a partnership with a manufacturer. Often easier said than done! Creators were frequently *"overwhelmed"* (C4, C8) by the number and complexity of production tools and methods, and how they must all fit together for successful production. C8 talked about his personal experience and mentioned, *"they asked me what color I wanted for the coating and I said green. Then they showed me dozens of greens tones to decide on."* R17 thought that *"there seems to be much more specialist knowledge in ... plastics, and then the manufacturing process for the plastics. ... more complex than just printed circuit boards."* C5 reported the same issue; *"it seemed to me that they were using another vocabulary. ... All these jargons were totally incomprehensible to an outsider like me at that time."* R18 reflected on a process of learning by trial-and-error: *"setting up, we haven't got a clue what we're doing. So we were sort of guessing... [If units fail] we don't even bother sending them back to the manufacturer because we don't really know what's normal..."* Lack of familiarity with the production process creates a huge disadvantage for creators since they are *"information have-nots"* (C7).

You can't learn it all from a textbook: Creators (C1, C2, C4, C7, C9) agreed that documented solutions and even the experience of others could be misleading. Even a small difference between projects—such as the finance available, the project timescale, the production volume, or the manufacturers' capabilities—may lead to large variations in best practice. For example, C4 recounted how their manufacturing process had been adapted: *"You won't find the alternative solution [they adopted] in a textbook."* Such knowledge is often gained through hands-on experience, akin to learning the art of tailoring by observing and practicing the craft firsthand (R18).

R21 explained how in the 1990s, before *"the hardware revolution and the ability to do startups and the availability of prototyping and things like that, [...] in large companies you would learn almost as an apprentice."* She observed that now *"the incubators and the accelerators are beginning to provide that material."* R17 added that his co-founder's *"education about manufacturing was sort of self taught, it came from watching endless videos online,"* but the fundamental drawback of this approach is that a hands-on experience is *"when those lessons are physically embodied in you, that's when you really literally internalize them..."* (R21).

A small fish in a big pond: Creators from big companies often experienced *"a feeling of losing the privileges"* (C9) when they left a reputable company to join an entrepreneurial team that was focused on small-batch products. Without the backing of an established brand, creators often find it hard to access quality service from suppliers and manufacturers. A related example was provided by C6 who used to work for an industry leader, where her requirements would always be satisfied by their spare parts suppliers in a timely manner. For instance, the sensors requested by her team would be customized with the highest priority and kept confidential until C6's team released the product. Now in a small start-up, she estimated the sensors available to them were two to three generations behind her former employer.

R18 gave a concrete example about trying to get a manufacturer to take low volume production seriously: *"it's very different if you are like someone at Microsoft approaching a company and they're all like, oh yeah, okay, right we'll do something. Or you're a PhD student and they're like, oh yeah, we know you don't have any money to make anything, why would we talk to you?"* This issue also surfaced with R15: *"A manufacturer like On [Semiconductor] or Bosch directly produces for Samsung, and Samsung can dictate what these chips should look like and no-one else gets to see these [chips]."*

4.2 Theme 2: Effective Communication Requires a Lot of Effort

Delivering instructions remotely is hard: During our interviews, most creators reported an unexpectedly high proportion of time spent on establishing a proper communication flow with manufacturers. They also complained about manufacturers' working pace and attitudes. C2 claimed that approximately two-thirds of his time and efforts were put into communication with their suppliers and manufacturers, even though as CTO he originally planned to focus on technical issues. This issue was further highlighted by C9, who described a frustrating remote working experience with her co-workers after her trip to the manufacturer was cancelled due to the outbreak of the coronavirus:

> *"I emailed them for a piece of specific information about the samples. All they needed to do was to read it from a sample produced there with my config file. Yet what they got me was a piece of random code. ... They hadn't sorted it out for three weeks. I can't remember how many emails I sent to them demanding a double check of their operating procedures. ... [Eventually] I asked them to repeat their operation to me in front of the camera that day. It turned out that they didn't use the config file I sent, but a default one. ... Honestly, it won't take me more than five minutes to solve the problem if I were there with them."*

In-person visits are better: Some creators in our study chose physical visits as a replacement for online communication, to solve issues and verify progress more effectively . This resonates with the idea that face-to-face communication is ideal for handling and processing more complex information [1]. R15 suggested that *"in many cases it is indeed much more helpful and a lot faster if you just go there."* When R17 manufactured his temperature logger in batches of 5,000 units he *"went to the factory in Malaysia and set up the process."* C6 described how her team members communicated their ideas with the sensor suppliers in Switzerland. They originally discussed the solution via an on-screen CAD model. However, it was hard to intuitively demonstrate the details of the design in this way:

> *"the CAD model is not intuitive enough. Some issues with assembling and disassembling are hard to perceive without experiencing the procedures personally. [...] Before the second meeting with them, my manager cut part of the 3D printed rig and brought it there. This significantly improved the efficiency of our discussion."*

Communications tools need to be better: When recounting the aforementioned experience, C6 expressed a keen interest in the adoption of advanced visualization techniques, which are currently flourishing in the IT industry, to present ideas or solutions in her domain. She cited the potential of augmented reality (AR) to allow stakeholders to delve into product models without an actual device on hand. Echoing this sentiment, C9 emphasized the challenges she faced in remotely analyzing circuit layouts She found it particularly taxing to convey detailed descriptions, geometries, and spatial associations via screen-based communication; it was far less efficient than in-person discussion. C5's predicaments further underscored the potential of integrating visualization tools in this field:

> *"You can ask them to take photos or shoot videos and send them to you, it's part of the service. The problem is that sometimes they can't shoot a video that clearly demonstrates all the details you are expecting. In this case, you won't be able to notice the imperfections until you receive the pieces. I remember once the manufacturers used octagon bolts for our prototypes, instead of the hexagon bolts we asked for. We didn't spot the issue from the video they sent to us since the image was really dark. You can ask them to show the workpiece during the video chat, but it's just not polite to ask them to 'perform like a robot arm rotating slowly' to display the workpiece, just so that you can find the issue. However, this is exactly what we need to properly judge the quality."*

4.3 Theme 3: Understanding the Manufacturer's Perspective

There may be a good reason behind every decision, but it's not always obvious: Our interviewees often recounted anecdotes of situations where they initially didn't understand things their manufacturing partners said or did. R21 commented that many hardware startup companies *"...have this sort of naive approach, 'well I'm just gonna hire somebody to do my electronics' without understanding that they need to understand how that's being done."* For example, C5 complained about a manufacturer he had used: *"They told me it was impossible to print a 1pt line on the free-form surface I designed. Later I learned that it was not impossible, just a bit tedious. They were simply not willing to spend time on such a small order."* C5 negotiated with the manufacturer on this particular detail and managed to defend his interest. However, the process took five times longer than he expected, which he later realized was *"not worth it"* and learned that *"you need to know where is the maximizing value point and stop there decisively"*.

Choosing a factory is not like choosing an IDE: Based on anecdotal evidence that came up repeatedly in our interviews, we learned that creators with limited experience consistently overlook transitional complexities. C10 considered choosing a factory for hardware production as being similar to choosing an integrated development environment (IDE) in software engineering, basing the choice on a list of features and specifications. This led him to misjudge variability in the production environment and the resulting quality, along with his control over production; ultimately he underestimated the lead time for his order. A similar case was shared by C1, whose production schedule was delayed when his manufacturer outsourced part of the work to another manufacturer (without telling C1!). Most creators initially struggled to understand that successful decision-making often relies on mutual intertexture and influence between multiple actors. C4 used the following analogy:

> *"Most issues in production are more complex than classification problems—you can't simplify develop an algorithm and let the computer decide. ... That's why human interventions, judgments, and innovations are required in this process."*

There are always two perspectives: As our creators shared their experiences, it frequently became apparent to us that some of their negative experiences were based on a lack of understanding of the manufacturer's perspective. For instance, C1 shared his experience of how the manufacturer he used squeezed processing cost in a way that ultimately affected product quality:

> *"They can be extremely astute, especially when they find you are just a newbie. For example, if you do not specifically ask, they would use a three-axis machine tool instead of a five-axis one to produce your workpiece, just because it's cheaper. They do this even though they know multiple setups [loading and unloading workpieces required by a three-axis machine tool] will decrease the machining precision."*

M11 voiced the opposite side of this issue, arguing that some of accusations from creators can be unfair: *"Surely we want to lower the cost as much as possible. But it's wrong for them to think every decision we made is for our own interest. Some new customers would ask if we can borrow the CMF design from Apple and they say 'I don't want anything complex, just make it look like an iPhone.' They have no idea how complicated it can be. Not to mention their [Apple's] production processes and parameters are top secret."* R22 summarized that *"at the point when you have to talk to that manufacturer, really understanding their motivation, your motivation, what they're trying to accomplish, what you're trying to accomplish; that's sort of having a really good relationship with your manufacturer."*

4.4 Theme 4: Prototyping is Nothing Like Production

Our intentional focus on issues related to communication via the semi-structured interview questions (see Appendix) gave rise to the three themes presented above. However, during our interviews sometimes the seed topics naturally led onto other discussion points. During our analysis we identified one particular group of issues which seem less related to communications, but which came up a lot, and which forms Theme 4. Indeed, when we asked our academic participants to rank the themes in Phase 2, Theme 4 emerged as the most important to them.

Production costs far out-weigh design costs: Prototypes with various forms and fidelities can be easily developed in design labs, since these places are usually full of resources for fast initial building processes—yet moving from the prototyping stage to the production stage requires more considerations due to differences between the development and production environments. As C4 recalled, *"we used a lot of wire cutting and stainless steel to create different shapes in school. It was expensive but the university could cover that. ... Now I use steel tubes instead, whenever it's possible. You need to cut, stretch, and weld them into the shapes you want. Sounds complicated but it's still cheaper than wire cutting."* R22 further commented that *"getting the prototype is almost like the 1% of effort required, and then the next step is almost like the 99%."*

The production process is surprisingly complex... Many of our creators lacked the experience to successfully trade-off product functionality with production capabilities: *"We kept adding more functions to our products and totally forgot that 'less is more' for a small team like us."* (C7). As a result, some creators were caught out by the difficulty of scaling hardware rich with features: *"The testing of subsystems is restrained by the development of other components, so we have to wait for the slowest team to finish the process, which frequently leads to delays in generating specifications. This always drives our suppliers and manufacturers crazy."* (C9). C10 shared with us how his first start-up company went into bankruptcy after a panoramic camera product had been delayed for more than a year:

> *"I developed a quite efficient and robust image mosaic algorithm and published a paper in a top conference. ... An alumnus of mine had some experience in action cameras, so we set up a start-up together and began developing a panoramic camera. I put too much faith in my algorithm, underestimating other deciding factors for the success of a product."*

...and there are many more places for things to go wrong: A "works-like, looks-like" prototype is unlikely to meet production-level standards, that is, it probably cannot be made with methods and materials of mass production. This kind of prototype is built in a strictly controlled environment by skillful prototypers, a process referred to as *slow-build.* Slow-build prototypers pay particular attention to details. *"They know which parts [of the sensor] are touchable, and which are not"* (C6). This is in contrast with the production environments for most artifacts that come off a production line. Therefore, prototypes cannot be used as a *"benchmark"* (C4, C10) to judge production samples. If a creator provides instructions to the manufacturer that do not match the expectations of operators on the production line, they may fail to follow them sufficiently carefully, leading to degradation of the product. Even shipping conditions may have to be specified tightly and communicated carefully:

> *"Once, the production samples sent to me didn't pass the performance test. I thought it was caused by processing issues since the prototype we built performed well. It must've been them neglecting some production procedures or environmental requirements during the process, but they claimed they did not and stopped the production. They have also asked us to fly there to check. We did and it turned out the sensors we shipped to them got damp somewhere on their way there. Shipping conditions would influence the sensor performance, and this seemed quite obvious afterwards. But that just never occurred to us at that time, since we built our prototypes here in the UK with newly-made sensors hand-delivered from suppliers."* (C6)

Every detail matters: Creators learned that their product requirements must be clear, leaving no room for misinterpretation. R21 stressed in particular the complexity of scaling up to production: *"People will say, 'Well this is just too complicated...' and I'm like, 'No, this is reality!' ... That attention to detail is so important."* If there was any ambiguity, or when creators were unable to effectively evaluate different options presented by manufacturers or decisions made by them, it could lead to *"unavoidable failures"* (C3). R18 illustrated this point with a specific example about how his team *"ended up then writing a QA [quality assurance testing] thing that basically put the devices on test for a week."* As pointed out by C1, *"there's no such thing as 'take that as an example' or 'just do it as they* *did'. Every new product is unique, no matter how ordinary it is. The production has to be innovatively tailored for each one."* That was also the reason why M12 turned down a request from a potential customer for pricing of a humanoid robot:

> *"He showed me a CAD model and some documents and asked me to estimate the manufacturing cost 'based on my experience'. I told him it's impossible to make such an estimation without delimiting the production volume specifications and information from component suppliers ... He later told me he was trying to apply for a research fund for a robot project. To convince the reviewers about the prospect of domestic robots, he had to prove that these robots could be inexpensive in the near future."*

5 The Academic Perspective

As mentioned above, after developing the four themes based on insights about the consistent challenges in hardware scaling from our Phase 1 industry practitioners, we found that the academics we talked to in Phase 2 had similar observations. In this section, we consider the significance of these challenges to device-based research in HCI. We question whether they manifest themselves in academic settings, and if they do, what benefits might arise from addressing them within the academic context.

5.1 Opportunities and Motivations from an Academic Perspective

Compared to the practitioners in the industry, some of the academics in our study were pleased to combine resources from their universities with their links to local industry to start the transition beyond their initial prototypes: *"when you spend most of your career sitting in a university where there's quite a lot of opportunity to learn, you can do the reading, you can do your own experimentation and things. You can develop your own expertise. I think that helps a lot. A lot of people won't have that opportunity"* (R16). Another resource that some academics mentioned was access to student help for low volume production! For example, R15 described preparing batches of around 80 smartwatches at a time in the way whenever his group needed to run a new user study.

R18 emphasized the significance of mass deployment of these academic creations. For these designers and researchers, it's not about the commercial viability of the product. Instead, it's about obtaining a deeper, more authentic insight into human experiences through these devices. He observed that today *"people haven't got a reason for making large numbers of devices, because it's never been a possibility"* but that *"this ability to make large numbers of devices will open up a space for HCI"* to generate deeper understandings and fill a current gap: *"we need to advance the understanding, not necessarily to make something that's gonna be sold."*

5.2 The Pros and Cons of an Evolving Landscape of Tools and Resources

Many of our academic participants made observations about the evolving landscape of tools and resources available to those making the transition from prototype to production, and how these were affecting the nature of that transition. R16 and R20 both recognised that modern prototyping tools speed up the development process, but questioned if this was always a good thing: *"All these super productive tools that we have... this produces much more noise."* (R20) and *"speed isn't always good, you know, and it takes some experience to slow down when the tools are trying to make you accelerate"* (R16). R20 thought that a by-product of this evolution was that the entire prototype-to-product lifecycle was becoming shorter– *"I think, this time span now is much shorter"* but suggested that they quality of each cycle was less than in the past. R16 and R20 also both quoted the same idiom *"if you only use a hammer, everything is a nail"* with R20 explaining that *"if you use Arduinos, you are not going to test things that Arduinos are not good at.'* and R16 warning that while initial prototyping stages might appear simpler now, there's an underlying concern that it might be subtly narrowing the breadth and depth of developers' thought processes.

R15 noted the dynamic nature of industries, emphasizing that tools in use can change swiftly, presenting continuous challenges for those on the ground. R18 echoed the sentiment, highlighting a glaring *"capability gap"*. He lamented the absence of avenues to acquire these essential skills. The few success stories, according to him, are either instances of pure serendipity, the expertise of individuals returning from the industry with a nuanced understanding of prototyping and production, or simply the tenacity of certain individuals. R21 chimed in with concerns about the educational approach, pointing out that students are often celebrated for finding *"the one right way"* rather than exploring potential pitfalls. Observing that the teaching methodologies, especially in fields like mechanical engineering, have remained stagnant for decades, she expressed concern that many educators lack first-hand industry experience. To bridge this gap, she proposed an exchange program where academics might immerse themselves in the industry for a few months, gaining practical insights and contextual understanding.

5.3 An Opportunity for New Types of Tool

In light of the insights from Section 4.2, we wonder what effect the prolific rise in remote working across many professions in the past few years will ultimately have on hardware product development. Certainly R20 was confident that many tasks could be performed remotely, suggesting that a significant blocker was simply *"lacking imagination how to do this remotely"*. There may be opportunities to speed up the adoption of remote collaboration practices in this domain through the development of new tools, something that the HCI community would be well-placed to help with.

The significance of refining processes and tools for information management becomes pronounced in remote collaboration. R21 told us that *"keeping a handle on all of the pieces of information that are interrelated and connected is a very big part of [effective scaling]. And the best companies that I have seen build the infrastructure for that data ahead of their growth. [...] they are putting in place the specification documents and they're engineering information systems and their linkages and their processes for double checking things ahead of when it becomes a problem."*. She went on to point out that while large companies typically use sophisticated software tools to help manage the complexity of productization, these are overkill for small companies who typically opt for lightweight general-purpose tools, such Google sheets. However, the latter doesn't have support for specific activities such as bill of materials tracking or managing quality test plans, which significantly limits its utility. R21 suggested *"there's a huge gap [...] it's definitely an area of opportunity."*

5.4 Scaling Provides a Powerful Route to Impact

All our Phase 2 participants were motivated to tackle the challenges of engaging with scaling through their desire for impact—R17 observed that *"you need to distribute in order to achieve some sort of impact."* R16 estimated that one of his projects had resulted in 7M units with upwards of 30M users; R18 had been responsible for around 100k units with an estimated user base of 500k to 1M via clinical studies. R17, who was similarly motivated by impact for his work, was frustrated that *"Academia is focused on publications [...] the paper that describes [my project] has like 200 citations and that's really good; if I tell someone that there's 40,000 of them out there and all those people spent \$50 on one, it kind of counts for nothing!"* R18 suggested that *"we probably need models of incentivizing people to do adoption style studies"* that would complement the user studies that are well-established when working with prototypes.

R15 valued the transition of a research project into a tangible product, highlighting its potential to ensure the continuity and reproducibility of research. He reminisced about the numerous projects and prototypes they'd developed that vanished with time: *"There's so many projects and prototypes that we've produced that are not around anymore. Basically we produced a paper around this, but we are not able to reproduce those results anymore. [...] Scaling up your prototype to a product allows you to ensure that this kind of survives."* When the primary users of a device are other researchers several participants noted that things were easier. Conversely, *"as soon as you are seen as a commercial company, then [...] people expect it to work" (R17).*

6 Opportunities for Supporting the Transition to Production

The insights reported by our interviewees reveal some of the inner complexities of the hardware scaling process. There are many factors to consider and complex inter-relationships between them [8], and there is no silver bullet for eliminating the complexity. However, it may be possible to bridge some of the gaps observed by our interviewees and in this section we present some ideas that emerged from our study.

Addressing the education and capability gaps: Our discussions with both industry practitioners and academics, especially underscored in *Theme 1: "Creating Relationships with Industry is Hard"*, paint a picture of the steep learning curve newcomers face in the field. While textbook knowledge lays the groundwork, it often falls short in real-world applications. Additionally, many academics highlight a disparity between academic syllabi and the genuine requirements of the industry. This disconnect, compounded by a lack of industry networking and hands-on experience, can lead newcomers to make early decisions that become barriers in their later hardware scaling endeavors.

In the past, apprenticeship programs in large corporations were instrumental in grooming the upcoming generation of professionals. However, with the recent stagnation in hardware innovation, many product-centric firms, with a greater emphasis on cost-efficiency than on ground-breaking advances, have neglected the essential role of mentoring and training fresh entrants. On the flip side, nimble incubators, with an eye on the future, have emerged, spearheading advancements in hardware innovation and facilitating its growth. Nevertheless, a persistent divide remains between academic instruction and practical capability, as highlighted in *Theme 3: "Understanding the Manufacturer's Perspective"*. Moreover, there's a tangible disconnect in knowledge sharing between the HCI community and industry practitioners. To counteract this compartmentalization of knowledge, fostering a continuous and active dialogue between academia and the industry becomes paramount.

Pioneering remote collaboration tools for the intermediary phase: Our interviewees' insights, as highlighted in *Theme 4: "Prototyping is Nothing Like Production"*, accentuate a more profound chasm between prototyping and production than initially perceived. The emergence of an intermediary phase, dubbed 'prototyping at scale' (R17), underscores a crucial yet complex and resource-intensive phase. Herein lies a promising avenue: the development of bespoke tools tailored specifically for this transitional phase, smoothing the progression from initial prototypes to large-scale manufacturing. The rapid expansion of AI- and data-driven manufacturing marketplaces, exemplified by companies like Bright Machines [29], Fictiv [13], and Xometry [45], underscores the potential here.

The sentiments expressed in *Theme 2: "Effective Communication Requires a Lot of Effort"* resonate with the urgent call for collaboration tools explicitly designed to cater to the unique challenges posed by hardware scaling. While current tools have their merits, they often fail to provide the instantaneous, coherent collaboration essential for brainstorming and troubleshooting. The vast potential of cutting-edge technologies like AR has remained largely untapped in the industrial landscape. This noticeable gap is not just a hurdle but a golden opportunity. It beckons the HCI community to ideate, pilot, and perfect pioneering solutions that align with the ever-evolving intricacies of hardware scaling.

Leveraging 'prototyping at scale' to delve deeper into real-world issues: Our study has underscored a recurring theme among academics: a hands-on engagement with 'prototyping at scale.' This methodology, entailing the deployment of devices on a grand scale, yields a treasure trove of data. Participants, recognizing the extensive scope of the study, displayed an increased propensity to share data. The ability to prototype at this magnitude fosters deeper participant immersion. Given the nature of many HCI studies—often centered around physical device interaction—hardware scaling emerges as a potent strategy. This approach amplifies the scope of experiments, integrating these devices seamlessly into users' daily lives. As participants interact with items reminiscent of mass-produced goods, they exude a sense of familiarity. Such interactions, grounded in everyday experiences, yield more authentic and valuable data for researchers.

Explorations within this framework can be multi-faceted, contingent upon the specific users of the technology under scrutiny. Whether the users are end consumers or fellow academics, their role delineates the context and direction of research. It offers insights into authentic challenges, sparking innovative research avenues within the HCI community. As HCI's influence permeates diverse sectors, from the Internet of Things (IoT) to healthcare, some studies will inevitably demand increased physical device interaction for data collection. This emphasis on large-scale and longitudinal deployment equips the academic world not merely to churn out products, but more crucially, to deepen their comprehension of prevailing phenomena, challenges, and real-world scenarios.

7 Discussion and Conclusions

7.1 Key Learnings

For a long time, the development of embedded systems and interactive devices has been divided into two main stages: prototyping and production. A plethora of research has been conducted to investigate and enhance the prototyping phase, but less attention has been given to the production stage. In this work, we carried out a two-phase study to explore issues that creators have to face when they attempt to scale hardware devices from a prototype to small batch production. We interviewed 22 practitioners in the interactive device field, including eight academics involved in the HCI/manufacturing community. Our interviews highlighted many transitional activities that are critical to a smooth transitional experience from prototype to production. The first phase of our analysis highlighted the following four recurring themes: (1) creating relationships with industry is hard; (2) communication requires a lot of effort; (3) understanding the manufacturer's perspective; and (4) prototyping is nothing like production.

Subsequent scrutiny showed that "prototyping is nothing like production" is perhaps the most significant of the areas we identified in terms of the extent of related activities and potential issues, especially for newcomers. Although our interviewees frequently expressed their journey as a transition from 'prototyping' to 'production', given the often-overwhelming complexity involved, it may be useful to break things down by grouping and naming a subset of the intermediate activities. We think of this new phase between prototyping and production as *isotyping*—making equal copies of a prototype. These *isotypes* would not be fully-refined, saleable products, but would none-the-less support additional testing and evaluation, as a precursor to full-on production. We believe that such an isotyping step would be a more manageable way to start addressing challenges associated with scaling, while raising awareness of others, but without the hard constraints of a production environment.

Finally, we also note that "communication between stakeholders" remains a consistent challenge—and one that underpins other related topics—despite the availability of modern collaboration tools.

7.2 Limitations and Future Work

We talked to interviewees with experience working on a wide range of products, including wearable devices, mobile phones, robots, drones, cameras, new displays, distributed sensing, physical computing devices, and home appliances, However, there are still many other product categories that have not been covered in our interviews so there will inevitably be a range of topics that were not surfaced. Although the experiences we did collect provided interesting insights, we would still would like to understand the broader perceptions and experiences of stakeholders within the prototype-to-product process.

Another limitation we encountered was the difficulty of eliciting rich feedback from manufacturers. We recognize the importance of deeper and broader engagement with manufacturers, particularly medium- to large-scale ones. However, our access was limited to small manufacturers referred to us by participants experienced in small-batch production, a group that sometimes faced communication challenges due to differing professional backgrounds or familiarity with research. While creators and academics demonstrated great interest in the study and a willingness to share and reflect on their experiences, manufacturers were less enthusiastic about discussing their experiences or offering suggestions to improve workflows and future partnerships. In future work, we aim to engage with a wider range of manufacturers, including those outside China, to capture more diverse perspectives.

From the experiences of our interviewees, we can clearly see how the falling cost of digital fabrication equipment, the increasing number of outsourcing services, and the tighter coupling between the digital and physical make it easier to commercialize designs via small-batch production. This echoes the HCI community's efforts to simplify products, increase process efficiency, strengthen communities [5]. Additionally, our university-based participants identified challenges specific to their academic context, along with a number of opportunities relating to hardware device scaling.

We see several avenues for fruitful future work. Firstly, the current study sampled a wide range of engineers and academics, allowing us to identify the major themes in this work. We see value in further work that goes deeper, either by conducting a series of interviews with practitioners in the interactive device field, or by carrying out longitudinal studies tracking the hardware scaling-up process through an entire development cycle. Secondly, our access was limited to small manufacturers referred to us by participants experienced in small-batch production. It would be interesting to engage with a wider and more comprehensive range of manufacturers and study in further detail the considerations they make and their internal constraints. Thirdly, we note that while there were substantial overlaps between the domains we covered, such as robotics, consumer electronics, and drones, future work could seek to identify domain-specific insights that can be translated into practical advice for future device creators. Our study did not focus on a single domain in this way, so our observations are naturally quite high-level. And finally, we are keen to explore further the concept of isotyping as a more manageable intermediate step between prototyping and production.

7.3 In Closing

We hope that the findings of this study will help those in the HCI community who currently work with novel hardware by increasing awareness of common challenges and pitfalls. We also found it interesting to learn about the potential for impact through scale from our academic participants. Finally, we hope to inspire others to envision, build and evaluate new tools, approaches, and techniques that contribute to the improvement of the product development experience and the subsequent success of embedded and interactive devices undergoing this transition.

Acknowledgments

We would like to thank our anonymous participants for their time and engagement. This work was supported in part by the UK Engineering and Physical Sciences Research Council [grant number EP/W020564/1].

References

[1] Thomas J Allen and Oscar Hauptman. 1987. The influence of communication technologies on organizational structure: A conceptual model for future research. *Communication Research* 14, 5 (1987), 575–587.

[2] Camilla Arndt Hansen and Ali Gürcan Özkil. 2020. "You Cannot Test It Before It Is Verified. When It Is Verified You Cannot Change It": Prototyping Challenges in Industry. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Vol. 83976. American Society of Mechanical Engineers, V008T08A043.

[3] Kusai Baroudi and Shukran Nasser Ibraheem. 2015. Assessment of chair-side computer-aided design and computer-aided manufacturing restorations: a review of the literature. *Journal of international oral health: JIOH* 7, 4 (2015), 96.

[4] Erling Bjögvinsson, Pelle Ehn, and Per-Anders Hillgren. 2012. Design things and design thinking: Contemporary participatory design challenges. *Design issues* 28, 3 (2012), 101–116.

[5] Leonardo Bonanni, Amanda Parkes, and Hiroshi Ishii. 2008. Future craft: how digital media is transforming product design. In *CHI'08 Extended Abstracts on Human Factors in Computing Systems*. 2553–2564.

[6] Malte Brettel, Niklas Friederichsen, Michael Keller, and Marius Rosenberg. 2014. How virtualization, decentralization and network building change the manufacturing landscape: An Industry 4.0 Perspective. *International journal of information and communication engineering* 8, 1 (2014), 37–44.

[7] Ludwig Bstieler. 2005. The moderating effect of environmental uncertainty on new product development and time efficiency. *Journal of Product Innovation Management* 22, 3 (2005), 267–284.

[8] David J Closs, Mark A Jacobs, Morgan Swink, and G Scott Webb. 2008. Toward a theory of competencies for the management of product complexity: six case studies. *Journal of Operations Management* 26, 5 (2008), 590–610.

[9] Luca Dezi Daniele Leone, Francesco Schiavone. 2018. Post-Campaign Operational Problems Hindering Promised Rewards in Crowdfunding Projects. In *Journal of Innovation Economics & Management*. 173–194.

[10] Marc Doussard, Greg Schrock, Laura Wolf-Powers, Max Eisenburger, and Stephen Marotta. 2018. Manufacturing without the firm: Challenges for the maker movement in three US cities. *Environment and Planning A: Economy and Space* 50, 3 (2018), 651–670.

[11] Sherif D El Wakil. 2019. *Processes and design for manufacturing*. CRC press.

[12] Joseph Feller, Patrick Finnegan, Brian Fitzgerald, and Jeremy Hayes. 2008. From peer production to productization: A study of socially enabled business exchanges in open source service networks. *Information Systems Research* 19, 4 (2008), 475–493.

[13] fivtic. 2024. Custom Manufactured Parts Done Right. https://www.fictiv.com/. [Online; accessed 9-December-2024].

[14] Verena Fuchsberger, Martin Murer, Manfred Tscheligi, Silvia Lindtner, Shaowen Bardzell, Jeffrey Bardzell, Andreas Reiter, and Pernille Bjorn. 2016. Fabrication & HCI: Hobbyist making, industrial production, and beyond. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. 3550–3557.

[15] David Philip Green, Verena Fuchsberger, Nick Taylor, Pernille Bjørn, David Kirk, and Silvia Lindtner. 2019. Introduction to this special issue on open design at the intersection of making and manufacturing. *Human–Computer Interaction* 34, 5-6 (2019), 379–388.

[16] Boston Consulting Group. 2021. 89% of People Expect Their Jobs to Be Partly Remote After Pandemic Ends, Global Workforce Study Showsz. https://www.bcg.com/press/31march2021-people-expect-jobs-partly-remote-after-pandemic-ends-global-workforce-study-shows. [Online; accessed 10-March-2022].

[17] Ollie Hanton, Michael Wessely, Stefanie Mueller, Mike Fraser, and Anne Roudaut. 2020. ProtoSpray: Combining 3D Printing and Spraying to Create Interactive Displays with Arbitrary Shapes. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–13.

[18] Jeffrey W Herrmann and Mandar M Chincholkar. 2000. Design for production: a tool for reducing manufacturing cycle time. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Vol. 35135. American Society of Mechanical Engineers, 261–270.

[19] Steve Hodges and Nicholas Chen. 2019. Long tail hardware: Turning device concepts into viable low volume products. *IEEE Pervasive Computing* 18, 4 (2019), 51–59.

[20] Steve Hodges and Mike Fraser. 2022. Citizen Manufacturing: Unlocking a New Era of Digital Innovation. *IEEE Pervasive Computing* 21, 3 (2022), 42–51.

[21] Microsoft Work Trend Index. 2021. The Next Great Disruption Is Hybrid Work—Are We Ready? https://www.microsoft.com/en-us/worklab/work-trend-index/hybrid-work. [Online; accessed 10-March-2022].

[22] Elina Jaakkola. 2011. Unraveling the practices of "productization" in professional service firms. *Scandinavian journal of management* 27, 2 (2011), 221–230.

[23] Lasse Skovgaard Jensen and Ali Gürcan Özkil. 2018. Identifying challenges in crowdfunded product development: a review of Kickstarter projects. *Design Science* 4 (2018).

[24] Rushil Khurana and Steve Hodges. 2020. Beyond the Prototype: Understanding the Challenge of Scaling Hardware Device Production. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–11.

[25] Yongsung Kim, Aaron Shaw, Haoqi Zhang, and Elizabeth Gerber. 2017. Understanding trust amid delays in crowdfunding. In *Proceedings of the 2017 ACM Conference on Computer Supported Cooperative Work and Social Computing*. 1982–1996.

[26] Michael Kimball. 2016. Manufacturing topical formulations: Scale-up from Lab to Pilot Production. *Handbook of Formulating Dermal Applications: A Definitive Practical Guide; Wiley: Hoboken, NJ, USA* (2016), 167–232.

[27] Zhuoxuan Li, Robert Eberhart, and Charles E Eesley. 2022. Maker Spaces, Entrepreneurship, and Institutions. *Entrepreneurship, and Institutions (February 28, 2022)* (2022).

[28] Silvia Lindtner, Shaowen Bardzell, and Jeffrey Bardzell. 2016. Reconstituting the utopian vision of making: HCI after technosolutionism. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. 1390–1402.

[29] Bright Machines. 2024. Robotics and AI: Building the AI Backbone. https://www.brightmachines.com/. [Online; accessed 9-December-2024].

[30] William Odom, Ron Wakkary, Youn-kyung Lim, Audrey Desjardins, Bart Hengeveld, and Richard Banks. 2016. From research prototype to research product. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. 2549–2561.

[31] Lawrence A Palinkas, Sarah M Horwitz, Carla A Green, Jennifer P Wisdom, Naihua Duan, and Kimberly Hoagwood. 2015. Purposeful sampling for qualitative data collection and analysis in mixed method implementation research. *Administration and policy in mental health and mental health services research* 42, 5 (2015), 533–544.

[32] Dusko Pavletic and Mirko Sokovic. 2009. Quality improvement model at the manufacturing process preparation level. *International Journal for Quality Research* 3, 4 (2009), 309–315.

[33] Corrado Poli. 2001. *Design for manufacturing: a structured approach*. Butterworth-Heinemann.

[34] Microsoft Research. 2020. New Future of Work. https://www.microsoft.com/en-us/research/event/new-future-of-work/. [Online; accessed 10-March-2022].

[35] Meghan Stockdale, Therese Okraku, Megan Brown, Jamie Miller, Bella Chiu, and Shelly Marston. 2020. Study of Impact on Information Worker Productivity.

[36] Evan Strasnick, Jackie Yang, Kesler Tanner, Alex Olwal, and Sean Follmer. 2017. shiftio: Reconfigurable tactile elements for dynamic affordances and mobile interaction. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 5075–5086.

[37] Jaime Teevan, Brent Hecht, Sonia Jaffe, Nancy Baym, Rachel Bergmann, Matt Brodsky, Bill Buxton, Jenna Butler, Adam Coleman, Mary Czerwinski, et al. 2021. *The New Future of Work: Research from Microsoft into the Pandemic's Impact on Work Practices*. Technical Report. Technical Report MSR-TR-2021-1. Microsoft.

[38] David R Thomas. 2006. A general inductive approach for analyzing qualitative evaluation data. *American journal of evaluation* 27, 2 (2006), 237–246.

[39] Anna C Thornton. 2021. *Product Realization: Going from One to a Million*. John Wiley & Sons.

[40] Thanh Tran, Kyumin Lee, Nguyen Vo, and Hongkyu Choi. 2017. Identifying on-time reward delivery projects with estimating delivery duration on kickstarter. In *Proceedings of the 2017 IEEE/ACM International Conference on Advances in Social Networks Analysis and Mining 2017*. 250–257.

[41] Gladys Tuo, Yi Feng, and Solomon Sarpong. 2019. A configurational model of reward-based crowdfunding project characteristics and operational approaches to delivery performance. *Decision Support Systems* 120 (2019), 60–71.

[42] Karl Ulrich and Steven Eppinger. 2011. *EBOOK: Product Design and Development*. McGraw Hill.

[43] Karl Willis, Eric Brockmeyer, Scott Hudson, and Ivan Poupyrev. 2012. Printed optics: 3D printing of embedded optical elements for interactive devices. In *Proceedings of the 25th annual ACM symposium on User interface software and technology*. 589–598.

[44] Jochen Wirtz, Martin P Fritze, Elina Jaakkola, Katja Gelbrich, and Nicole Hartley. 2021. Service products and productization. *Journal of Business Research* 137 (2021), 411–421.

[45] Xometry. 2024. Manufacturing on Demand. https://www.xometry.com/. [Online; accessed 9-December-2024].

A Appendix

Table 3: The high-level flow of interview questions used in Phase 1. Any variations for manufacturers are shown in brackets.

- *Tell me about your background.*
- *Tell me about your experience with electronic device development in terms of the type of device, production volume, manufacturing processes involved, etc.*
- *Describe your workflow for a project. What software, tools and processes do you leverage?*
- *Do you look for particular qualities when selecting a manufacturing partner (**or** agreeing to help a device creator)?*
- *Do you work with overseas manufacturers (**or** customers)? What are the pros and cons?*
- *Throughout a project, how often do you talk to manufacturing partners (**or** device creators)?*
- *How do you usually explain or demonstrate ideas, issues or task status to each other?*
- *What are the most frequently discussed topics and issues? What are the most and least important?*
- *Do manufacturing partners (**or** customers) typically understand the requirements for a product (**or** the requirements of a manufacturing processes) quite quickly?*
- *During a project are there common areas of misunderstanding or things that can easily go wrong? If so what are they and when do they occur?*
- *Are there tasks that need multiple rounds of discussion and optimization?*
- *Do you find that some issues are best discussed face-to-face, and if so which? How much face-to-face time is needed to address them?*
- *Have you seen any evolution of tools or techniques that assist with the prototype to product transition?*
- *Can you describe a future vision for better tools or techniques that mitigate problems you've witnessed? What are the challenges making these real?*

Table 4: The high-level flow of interview questions used in Phase 2.

- *Tell me about your background.*
- *Tell me about your experience with electronic device development in terms of research goals, the type of device and how many you made, the manufacturing processes involved, etc.*

[Themes from Phase 1 of the research presented to interviewee.]

- *Please rank the themes in order of significance to you, explaining your rationale.*
- *Do any of the themes not resonate with your experience or knowledge?*
- Are any themes missing?
- *Given what we have talked about so far, do you think these issues are well-defined, explored or expressed in the literature?*
- *How would a newcomer trying to translate their prototype to mass production find appropriate information and guidance?*
- *If you think back to when you were a newcomer, how did you obtain the information and guidance necessary?*
- *In your opinion, do you think any of these problems have been solved or mitigated in the past few years?*
- *In your opinion, do you think this topic of scaling device prototypes is relevant to the HCI community?*
- *Do you think there's enough attention on this process and the issues therein in the HCI community? If not, how can we improve the awareness of these issues in the HCI community?*
- *Can you see HCI/manufacturing research trajectories that could help mitigate these issues, such as new methods, tools, case studies, etc.? What are these?*