INTERNATIONAL DESIGN CONFERENCE – DESIGN 2022
https://doi.org/10.1017/pds.2022.22

Design by Prototyping: Increasing Agility in Mechatronic Product Design through Prototyping Sprints

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Abstract
This paper adapts the agile scrum sprint, typically used in software development, to a prototyping sprint for mechatronic product design. The Design by Prototyping framework describes how the prototyping sprint can be used to manage the prototyping process in design projects through an agile-stage-gate hybrid model. A comparison of 18 student projects using either prototyping sprints or a traditional iterative prototyping approach shows that prototyping sprints helped students make more deliberate, strategic decisions about their use of prototypes.

Keywords: prototyping, agile development, design process, design models

1. Introduction

"Acting as though the development process is defined and predictable results in being unprepared for the unpredictable results". This was one of the arguments used by Ken Schwaber when he first introduced the agile framework 'scrum' as an alternative to conventional development models such as the stage-gate process (Schwaber, 1997). The fact is that new product development is rarely predictable - now less than ever as companies must move at a rapid pace to stay competitive in a global market (Cooper, 2014). However, when we use gated development models, we act as if we can define and plan the entire development process for a new product at the beginning of the project. As a result, the likelihood of succeeding decreases because we become unable to react to changes (Schwaber, 1997).

Agile approaches, such as scrum, describe how to deliver value in incremental steps called 'sprints' (Schwaber and Sutherland, 2020). Each increment provides an opportunity to adapt the product and change design direction if needed. Scrum has become popular in software development ("The State of Scrum 2017-2018," 2017) and recently hardware companies have also started to use agile approaches to increase their efficiency and responsiveness (Cooper, 2014). For software products, an increment can be a new feature that is ready to be released in a software update at the end of the sprint, so value is created immediately. However, a key challenge for hardware development is that a physical product cannot easily be delivered to customers in increments. Some companies have combined features from agile and stage-gate models, thereby creating so-called 'agile-stage-gate hybrids' that have shown to increase performance compared to traditional stage-gate models (Cooper, 2014; Edwards et al., 2019; Sommer et al., 2015). In agile-stage-gate hybrid models, scrum sprints are done within each project phase, see Figure 1. At the end of a sprint, "something tangible" is produced to receive feedback from internal and external stakeholders (Edwards et al., 2019). Prototypes allow companies to test and evaluate a product during its development, even though the product is not yet deployable. Therefore, prototyping plays a key role in adapting agile for hardware development (Böhmer et al., 2017), but there is still relatively little literature detailing how to use prototypes in agile hardware projects. This is the first research gap that will be addressed in this paper.

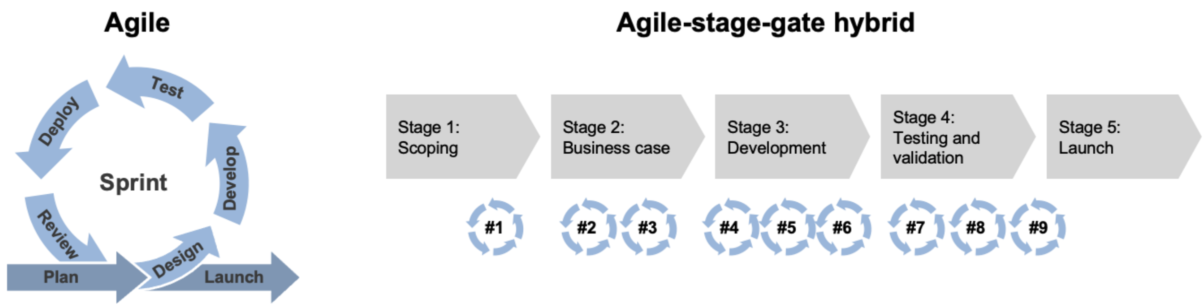

Figure 1. Agile sprint and an agile-stage-gate hybrid model. Figure based on Edwards et al. (2019) and popular representations of agile (e.g. Goddard, 2021)

Simultaneously, recent literature on prototyping in design has highlighted the benefits of prototyping early, iteratively, and continuously across project phases (Campbell et al., 2007; Dutson and Wood, 2005; Menold et al., 2017). A prototype is no longer seen only as a detailed functional model validating a product's technical performance at the end of the project, but as any type of model (mock-up, computer simulation, paper prototype etc.) used to explore, evaluate, or communicate a part of the product related to the product's busines viability, user desirability, or technical feasibility (Lauff et al., 2018; Menold et al., 2017). A result of these developments is that the state-of-the-art prototyping process, illustrated in Figure 2, shares many similarities with agile models, even though prototyping literature rarely link them to agile theory. Another consequence of this broadened understanding of prototype usage is that design practitioners can be challenged in deciding why, what, and how to prototype during design projects (Diefenbach et al., 2019). This is the second research gap addressed in this paper, for novice designers.

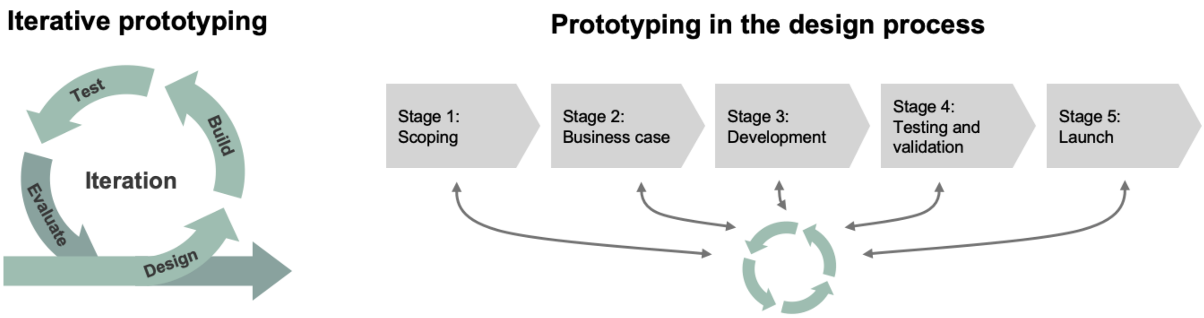

Figure 2. Iterative prototyping in design shares many similarities with agile models. Figure based on (Campbell et al., 2007; Menold et al., 2017; Thomke, 1998)

This research bridges agile and prototyping literature by adapting the scrum sprint to a prototyping sprint for mechatronic design projects. This contributes to the identified research gaps by 1) detailing how to use prototype in agile-stage-gate projects and 2) providing a framework for managing the prototyping process. The research questions are:

1. *How can the agile scrum sprint be adapted for prototyping in mechatronic design projects?*
2. *How do prototyping sprints affect novice designers' ability to use prototypes strategically during mechatronic design projects compared to an iterative prototyping approach?*

The paper is structured as follows: Section 2 introduces the Design by Prototyping framework and the prototyping sprint based on existing agile and prototyping theory, section 3 compares mechatronic projects structured with a simple iterative prototyping process and projects structured with the prototyping sprint, and finally, section 4 discusses the results and implications of the research.

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2. Prototyping sprints for mechatronic design projects (RQ1)

This section adapts the scrum sprint to the prototyping sprint. Then, the Design by Prototyping framework describes how prototyping sprints can be used in mechatronic design projects.

2.1. The prototyping sprint

Figure 3 shows the prototyping sprint, which we adapted from the scrum sprint as described by Schwaber and Sutherland (2020). We define the prototyping sprint as a time-limited prototyping cycle used to deliver a prototyping milestone that tests the most critical assumptions about a product's desirability, viability, or feasibility at a given time in the project. The prototyping sprint has a fixed duration, typically 1 to 4 weeks. Thereby, the final product is developed through a series of prototyping cycles that decrease risk in the process by validating the most critical aspects of the design.

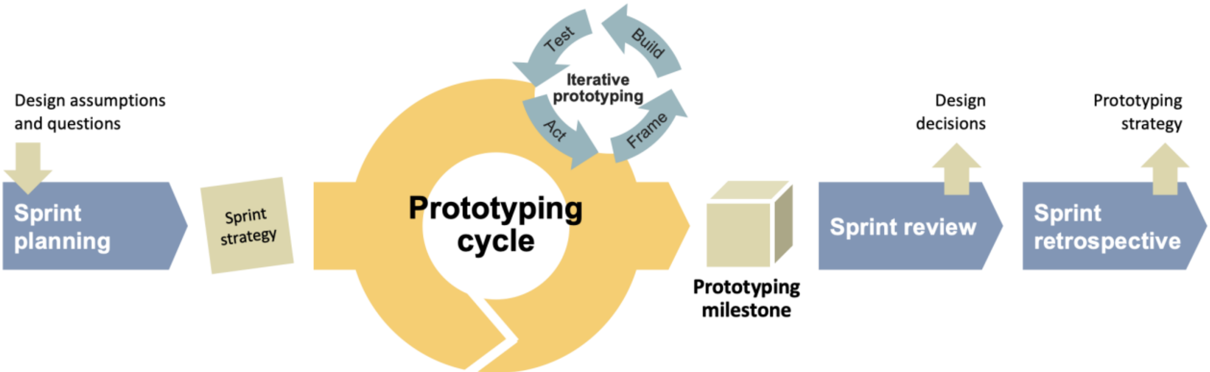

Figure 3. The prototyping sprint adapts the scrum sprint for mechatronic product development (the figure is based on common illustrations of scrum)

The sprint begins with a ***sprint planning*** event where the development team defines a focus and creates a ***prototyping strategy*** for the sprint that describes why, what, and how to prototype during the cycle:

- **Why:** The team formulates a sprint goal to describe what they want to achieve with the sprint.
- **What:** The team identifies, prioritises, and selects key design questions or assumptions to answer during the sprint. The team should also consider which part of the mechatronic product they are designing and testing, e.g. which sub-systems, functions, or concepts.
- **How:** The team considers their prototyping strategy and the types of prototypes that can help them design and evaluate the parts of the product in focus. Important factors to consider in a prototyping strategy are e.g. use of iterations, parallel prototyping, level of fidelity, integration or isolation of systems, physical scaling, and use of physical or virtual prototyping (Christie et al., 2012). The team should also create a plan for the sprint.

To prototype strategically means making deliberate decisions about the use of prototypes to achieve project goals during a design project. The prototyping strategy defines how prototyping is used to achieve the sprint goal during the prototyping cycle.

During the ***prototyping cycle***, the development team makes several smaller ***prototype iterations*** to reach the ***prototyping milestone*** that achieves the goal selected at the planning of the sprint. In Figure 3 the larger circle (yellow) refers to the overall prototyping cycle leading to the prototyping milestone, while the smaller circle (teal) refers to the iterative prototyping. Figure 4 shows the detailed prototyping process for a cold brew coffee maker, where many smaller prototype iterations were made and then integrated at the end in the final prototyping milestone. This example illustrates how prototyping cannot be presented as a simple iterative process, but that iterations can happen in parallel, be integrated with each other, and employ different types of media. Thus, the prototyping cycle consists of many smaller iterations used to explore and evaluate different designs. The prototyping milestone is the sum of these iterations. The prototyping milestone can be one full physical model, which integrates the prototype iterations done during the cycle, but it can also be multiple models used for different parts of the product.

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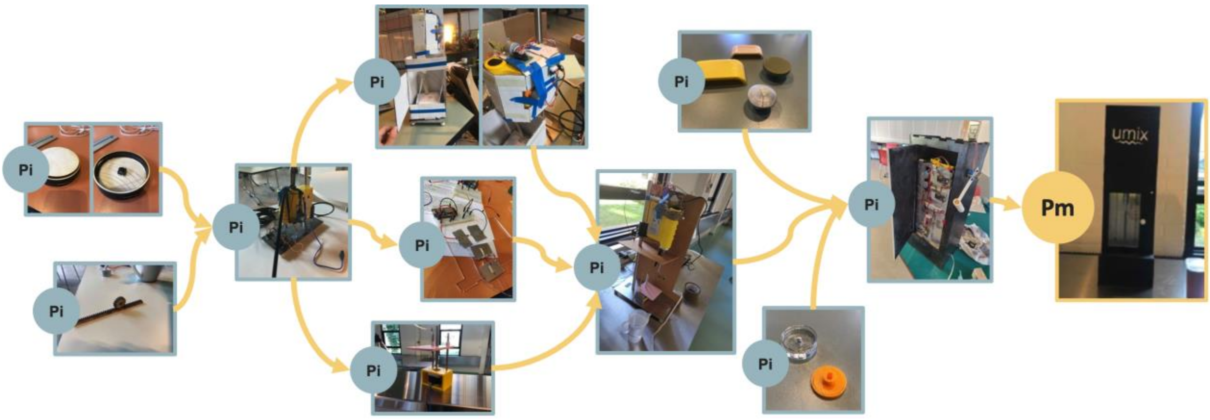

Figure 4. A three-week prototyping process for an ultrasonic cold brew coffee maker. Prototype iterations (Pi) were used to reach the final prototyping milestone (Pm)

At the end of the sprint, the prototyping milestone is formally ***reviewed*** by internal and external stakeholders to gather feedback for the further development. During the iterative prototyping cycles, several more or less formal design decisions have been made to explore and evaluate designs. The sprint review is an opportunity to make formal decisions based on prototyping results and to change design direction if needed. The development team also conducts a ***sprint retrospective*** where they consider how to adjust their strategy for the next sprint and how to improve their overall prototyping strategy.

2.2. Design by Prototyping framework

This paper is titled 'design by prototyping' because it fully embraces the understanding of prototyping as a tool *to design* rather than a tool to just *test a design*. The idea that prototypes are used to test a 'finished design' leads to increased risks of waiting to prototype until late in the design process. When we understand prototypes as manifestations of designs, it becomes impossible to design anything without using prototypes. With prototyping sprints, the development process is manifested through a series of prototyping milestones that each progress and detail the design further. The Design by Prototyping framework in Figure 5 shows how prototyping sprints are integrated into the design process.

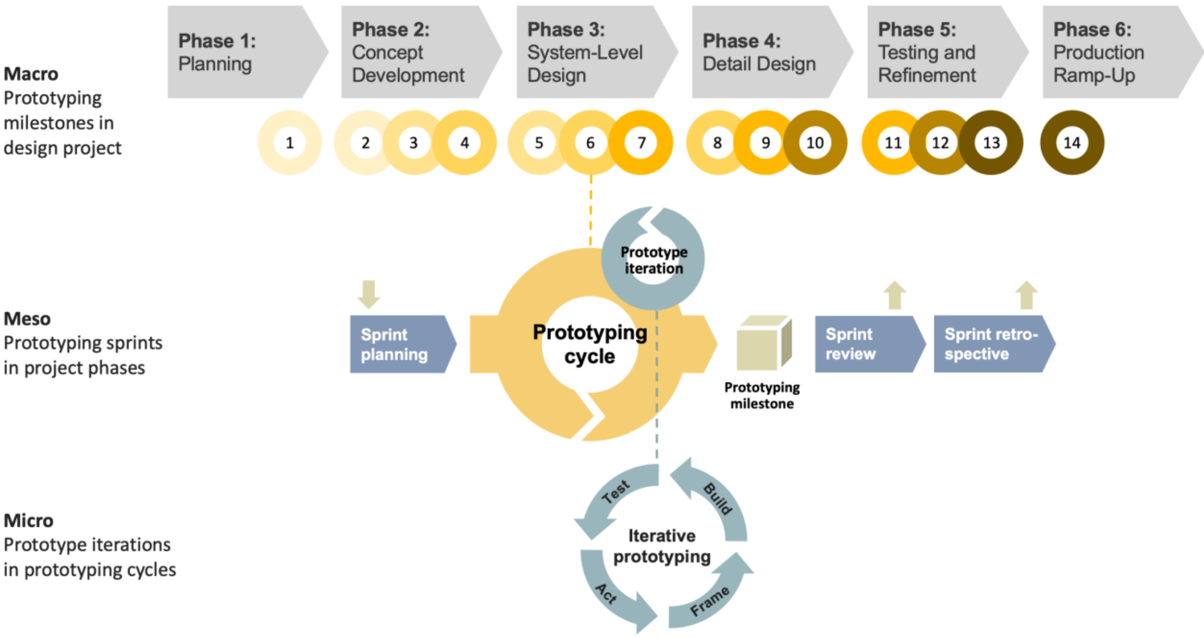

Figure 5. Prototyping sprints are used in each project phase of the Design by Prototyping framework. Prototype iterations are part of a prototyping cycle to reach prototyping milestones

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Through prototyping sprints, the prototyping process is managed at three levels of abstraction: The macro scale considers prototyping sprints in the design project to create the final product, the meso scale covers a prototyping sprint to create a prototyping milestone, and the micro scale covers a prototype iteration (Hansen and Deininger, 2021). The macro scale prototyping process is planned at the beginning of the project and prototyping sprints are used continuously from the beginning of the project until launch. At the beginning of a project the prototyping sprints, the length of a sprint, and important milestones can be planned, but the detailed scope of the sprints cannot be decided. The sprint goal and key questions selected for a prototyping sprint should be based on the project objectives at the time of the sprint, and the results from a prototyping sprint should result in decisions on a project level.

The prototyping sprints always include the same steps, but progress over time in the types of assumptions that they test. For instance, prototyping sprints at the beginning of the project should focus on validating assumptions about the technical feasibility and overall market fit, while the later prototyping sprints should validate the detailed technical systems and usability. Similarly, there will be a progression in the types of prototypes that are used, for instance in the fidelity level, which should bring prototypes closer to the final product. This progression is illustrated through the prototyping sprints in Figure 5.

3. Comparison of iterative prototyping and prototyping sprints (RQ2)

In the previous section, the prototyping sprint was introduced. This section compares prototyping sprints with the iterative prototyping approach to evaluate how the approaches affected student teams' ability to make deliberate decision about their use of prototypes during mechatronic design projects.

3.1. Methods

Design of Mechatronic Systems is a mandatory course for 4th semester engineering design students at a large European technical university. In the last part of the course, student design teams develop new mechatronic products during a 3-week period. Here, there are almost no lectures or mandatory activities, and the teams spend most of the time designing, building, and testing their products. During the course, the teams are asked to describe their design process in an online blog. At the end of the course, they present a functional prototype including electronics, software, and mechanical components. Examples of mechatronic products from the course are a tofu maker, a spice dispenser, a device to monitor water usage in the shower, and the ultrasound coffee brewer shown in Figure 4. In this research, mechatronic projects from two courses were compared, see Table 1. In one course the teams used an iterative prototyping approach, and in the second course they used prototyping sprints.

Table 1. Design for Mechatronic Systems course

Prototyping approach	Iterative prototyping	Prototyping sprints
Year	2019	2021
Teams	10	8
Students	60	56
Prototyping support	Prototyping Planner (V2)	Prototyping Planner (V4) and ProtoMap

3.1.1. Different prototyping approaches

Different prototyping approaches were presented to the students in a lecture at the beginning of the 3-week project, see Figure 6. In 2019, an iterative prototyping approach was used throughout the three weeks and the teams were supported by the 'Prototyping Planner' tool (Hansen et al., 2020). The Prototyping Planner is a one-page template used to plan and identify results from a prototype iteration. The template is divided into four areas: 1) Frame, 2) Build, 3) Test, and 4) Act with specific questions guiding the user to frame the prototyping activity, plan how to build the prototype, plan how to test the prototype, and to identify results after the prototype is tested. In iterative prototyping, the results from one prototype will spark a new prototyping activity for an adjusted design until the final prototype or product is reached. In the 2019

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course, the teams used the Prototyping Planner for the micro scale iterative prototyping process, and there were no requirements for how many iterations they should have.

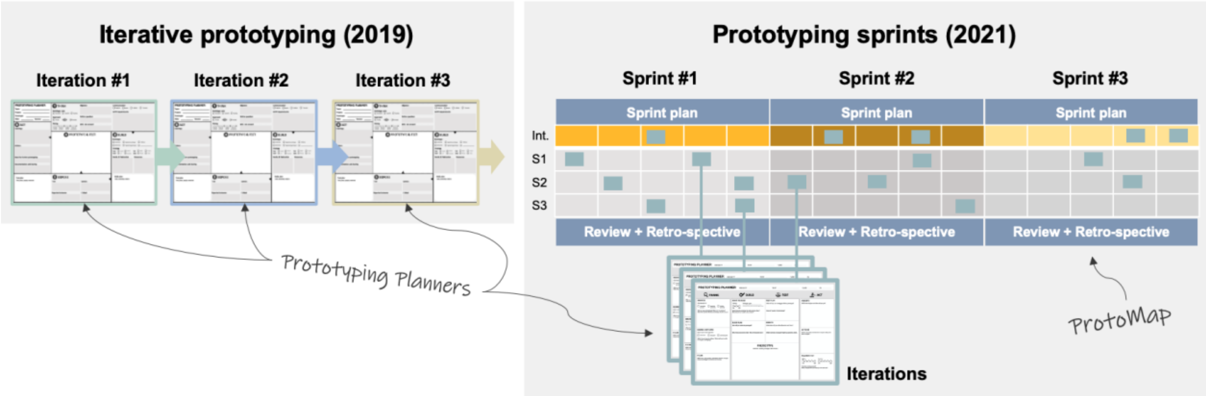

Figure 6. Comparison of prototyping approaches and support in the two courses. Prototyping Planner templates and a ProtoMap example can be found at www.prototypingplanner.com

The 2021 course was structured in three 1-week prototyping sprints and the teams used both the Prototyping Planner and the 'ProtoMap' (Hansen and Özkil, 2020). When prototyping sprints are used, iterations on the micro scale are part of a prototyping cycle leading to a prototyping milestone on the meso scale. Therefore, a ProtoMap tool was used to 'connect' the prototype iterations (≈ Prototyping Planners). The ProtoMap structures the prototyping process on two axes. The horizontal axis depicts a timeline of prototype iterations. The vertical axis shows which part of the product a prototype refers to. For mechatronic products, a systematic approach to prototyping is important to ensure that different parts of the system can be developed in isolation but still be integrated with other sub-systems. Prototypes that focus on the integrated product are placed above the horizontal axis, while prototypes for different sub-systems are placed below the horizontal axis. A picture and a reference number were used to link the prototype iterations on the ProtoMap with the corresponding Prototyping Planners. At the beginning of each sprint, the teams defined a sprint goal, selected key questions, and considered their prototyping strategy. At the end of a sprint, they reviewed their prototyping milestone and retrospectively evaluated their prototyping process. Space was added at the top and bottom of the ProtoMap template for the students to document the results of their planning and reviewing activities.

3.1.2. Analysing strategic prototyping processes

This analysis focusses on the teams' ability to use prototypes strategically during mechatronic design projects. The desired effect from following the structured prototyping approaches is that the teams make deliberate decisions on why, what, and how they prototype, rather than prototyping randomly. The prototyping tools were used both as support for the teams, but also as documentation. Thus, the prototyping decisions in the two courses were compared through 1) a computational and manual analysis of word usage on the online design blogs and 2) observation of strategies shown on the ProtoMaps.

3.2. Results

At the end of the two courses, 116 students presented functional prototypes for 18 new mechatronic products. These 'final prototypes' had been developed through 532 prototype iterations documented on 8 ProtoMaps and 396 Prototyping Planners. Figures 7 and 8 show an example project from each course.

The manual analysis of the design blogs compared word counts within three categories: **Project words** describing the purpose of activities in relation to the design project (plan, process, goal, focus, purpose, question, priority/ies, milestone, objective, vision), **strategy words** describing specific factors in a prototyping strategy (iterate/ion, parallel, integrate/ion, isolate/ion, fidelity, physical, virtual, scale, strategy/ic), and **fabrication words** related to the construction of mechatronic prototypes (motor, sensor, code, nodered, nodemcu, arduino, mechanism, CAD). The manual comparison of project, strategy, and fabrication words in

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Figure 9 shows that when prototyping sprints were used, the teams focussed a little less on describing the construction of their prototypes, but instead described the purpose of their activities and their chosen prototyping strategies more. In fact, they used more that 13 times as many words to describe their prototyping strategies than the teams who used iterative prototyping, even though all teams had received an introduction to the strategies, and they were explicitly listed on the Prototyping Planner in 2019.

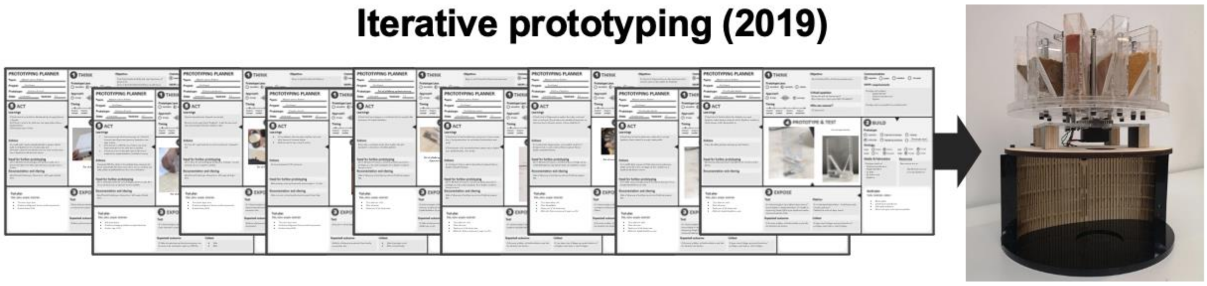

Figure 7. The spice dispensing machine was prototyped in an iterative prototyping process documented on nine Prototyping Planners. Each Prototyping Planner describes the purpose and outcome from a prototype iteration, for instance a test of whether the stepper motor moved to the proper place for the spice needing to be dispensed.

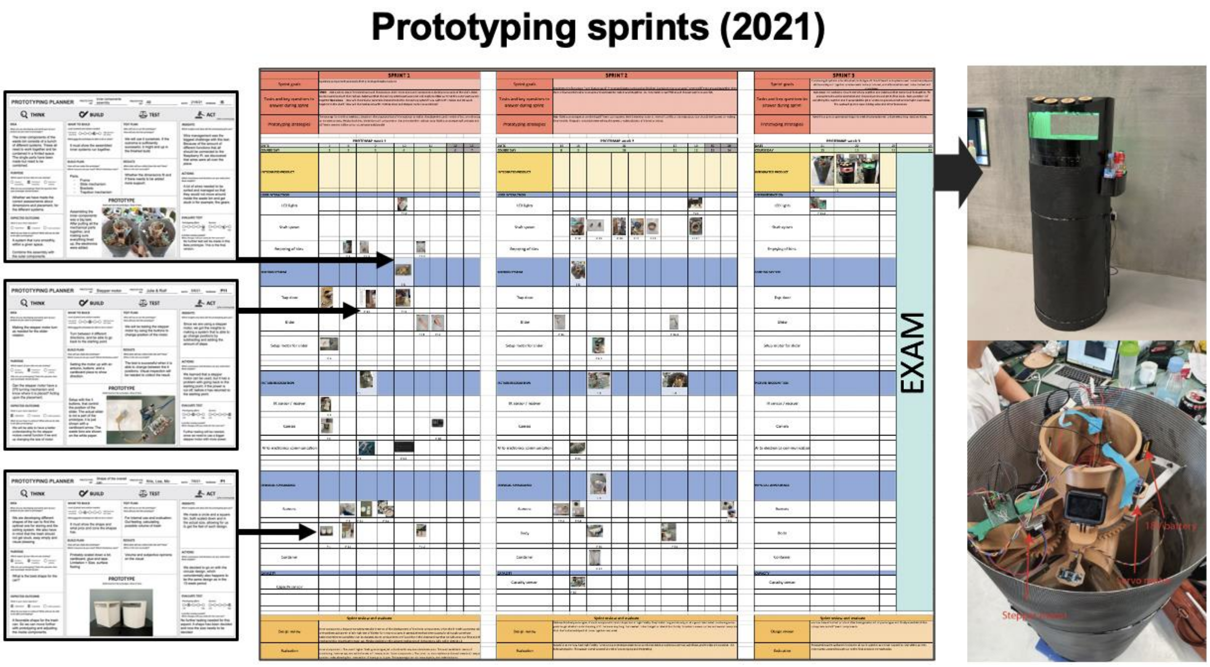

Figure 8. The automatic waste sorting bin was prototyped through three prototyping sprints. The ProtoMap shows that the bin was divided into five modules (blue rows) that were prototyped in parallel and fully integrated at the end of the third sprint (yellow row). Three of the 48 used Prototyping Planners are shown with arrows marking corresponding iterations on the ProtoMap. The red area above the ProtoMap describes the plan for the sprint and the orange area below describes the results of the sprint review.

The computational approach to determining the most meaningful words in each year was formulated as a classification task – to determine which words were most useful for predicting whether a blog was written in 2019 or 2021. Most of the blogs from 2019 were written in Danish, and thus were translated into English via Google Translate. All blogs were then preprocessed and lemmatized using spaCy (Montani et al., 2021), followed by a scikit-learn (Pedregosa et al., 2011) pipeline of Term Frequency-Inverse Document Frequency (tf-idf) (Sammut and Webb, 2010) and a chi-squared test for feature selection (Manning et al., 2008). The highest chi-squared test statistics indicate the terms that best differentiate the 2019 and 2021 blogs. The tf-idf vectorizer used the L2 norm, sublinear term frequency scaling, and a minimum cutoff of 5 words must be present in the corpus. Like the manual

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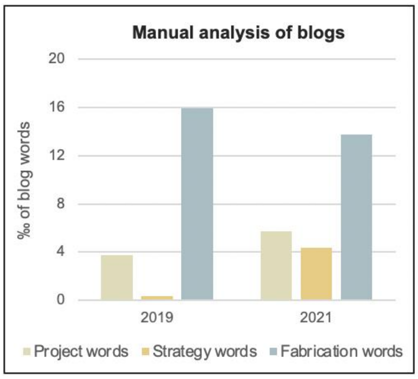
analysis, a shift from fabrication focus to strategy focus is found in the computational analysis in Figure 9. In the top 20 words that best differentiate blogs from the two courses, 2019 blogs can best be identified with fabrication words, while strategy words are most useful to identify 2021 blogs.



Computational analysis of blogs (top 20 words)							
Most useful words to predict 2019 blogs				Most useful words to predict 2021 blogs			
Words	χ2 statistic	2019 count	2021 count	Words	χ2 statistic	2019 count	2021 count
engine	0,4465	64	0	sprint	0,8130	1	130
liquid	0,4188	48	0	fidelity	0,5690	0	44
june	0,3956	182	10	integrated	0,4996	0	30
machine	0,3748	149	3	beta	0,4669	0	29
container	0,3657	277	4	iteration	0,3801	3	31
dispense	0,3340	71	0	battery	0,3705	2	79
mix	0,3307	46	0	strategy	0,3628	0	16
comment	0,3257	104	2	protomap	0,3478	0	16
categorize	0,3242	47	0	subsystem	0,3216	3	48
				integrate	0,3110	2	31
				esp	0,3101	7	59

Figure 9. Manual word count (left) and computational analysis (right) of online design blogs

The design blogs show how the teams *described* their strategies, but the ProtoMaps and Prototyping Planners show how they *used* them in practice. To compare use of prototyping strategies, the number of iterations, parallel prototypes, defined sub-systems, and integration prototypes were counted from the. ProtoMaps. The teams in 2019 did not develop ProtoMaps themselves, but their Prototyping Planners were adapted into ProtoMaps in previous research (Hansen and Deininger, 2021). The comparison of the documented processes in Table 2 shows that teams that used prototyping sprints iterated more overall, defined more sub-systems, iterated more within their defined sub-systems, and used more prototypes to integrate sub-systems.

Table 2. Comparison of strategic factors for an average team

Strategic factor	Iterative prototyping (2019)	Prototyping sprints (2021)	Conclusions for 2021
Iterations (Prototyping Planners)	13.5	32.6	More (documented) prototype iterations
Iterations (on ProtoMap)	-	49.6	
Sub-system level 1 (e.g. module)	4.0	5.6	More sub-systems defined
Sub-system level 2 (e.g. parts)	3.9	11.6	
Sub-system level 2 / level 1 (e.g. number of parts per module)	1.0	2.1	
Iterations per parallel prototype	2.2	4.4	More iterations within sub-systems
Integration prototypes	8.9%	10.1%	More prototypes to integrate sub-systems
Teams that used integration prototypes	50%	88%	

The teams that used prototyping sprints prototyped 267% more than teams that used iterative prototyping according to the ProtoMaps, or 142% more according to their Prototyping Planners. A Prototyping Planner may include several smaller iterations, which explains the difference in iterations between ProtoMap and Prototyping Planners. The use of the ProtoMap in prototyping sprints therefore led to a more transparent and detailed documentation of the prototyping process. Using the ProtoMaps from the first sprint planning also meant that the teams had to consider how to divide their product into different sub-systems that could be prototyped in parallel. Defining more sub-systems is not necessarily better, but the fact that the teams iterated more within their defined sub-systems indicates that they made a better definition of systems than the teams in 2019, where they only re-iterated each sub-system 1.2 times on average. Finally, the use of prototyping sprints also caused an increase in the number of teams that deliberately used prototypes to integrate sub-systems. Overall, the results indicate that structuring the prototyping process with prototyping sprints led to a more deliberate and transparent process.

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4. Discussion

This paper adapted the agile scrum sprint to a prototyping sprint for mechatronic design and showed that prototyping sprints led to a more strategic prototyping process compared to iterative prototyping.

4.1. Contribution and implications

The Design by Prototyping framework was presented to describe how prototyping sprints can be used to increase agility in mechatronic design projects. The framework bridges agile and prototyping theories that have been moving towards each other in recent years, but rarely have been fully connected in literature (such as Menold et al., 2017 and Sommer et al., 2015). From an agile perspective, the prototyping sprint should not be understood as an alternative version of scrum, but rather as a specification of prototyping in scrum. From a prototyping perspective, the prototyping sprint provides a structured framework for managing the prototyping process in design projects. Design by Prototyping can be used as a standardised methodology by both novice and expert designers working with multi-disciplinary teams to develop complex products.

The results from this paper show that using prototyping sprints increased novice designers' abilities to prototype strategically and deliberately during the design process. Teams that used prototyping sprints described chosen prototyping strategies and related their activities to the overall design project more than teams that used an iterative prototyping approach. Additionally, their documented prototyping processes were more transparent, detailed, and systematic, showing an increased or improved use of selected strategic factors. The results indicate that the iterative prototyping process is too simplified to use as a basis for managing the prototyping process and only works for high-level prototyping milestones or a few detailed prototype iterations. The bigger perspective may be forgotten when the step-by-step prototyping approach is used. We posit that the improved performance of prototyping sprints is caused by the formal sprint planning and reviewing events that ensure that prototype iterations follow project objectives, while leaving room for unexpected results. This research also validated the use of the ProtoMap for structuring the prototyping process live, and not just for retrospective analysis (Hansen and Özkil, 2020).

Our findings contest the understanding that prototyping is a tool used after the completion of a design. Instead, the Design by Prototyping framework suggests that a product is designed and evaluated through different types of prototypes that manifest in the final design - design by prototyping.

4.2. Limitations and future work

Some limitations exist for the evaluation of prototyping sprints in this research. The comparison relied on the teams' own documentation and there might be a difference in the documented prototyping process compared to their real process. Additionally, design blogs were written in both Danish and English which was accounted for but may have influenced the blog analysis. To counteract these limitations, multiple types of data analyses were used, which showed similar results. This research evaluated the impact of using prototyping sprints on novice design teams' prototyping activities during three-week projects. Future research should implement prototyping sprints in longer projects, in industry contexts, and evaluate the impact on project outcome and effectiveness.

4.3. Conclusion

Developing products through time-limited sprints allows design teams to adapt to unexpected results during the design process. In this paper, the agile scrum sprint, typically used in software development, was adapted to a prototyping sprint for mechatronic product design. The Design by Prototyping framework describes how the prototyping sprint can be used to manage the prototyping process in an agile-stage-gate hybrid model. A comparison of 18 student projects using either prototyping sprints or a traditional iterative prototyping approach suggests that prototyping sprints, and the prototype support tool 'ProtoMap', helped students make more deliberate, strategic decisions about why, what, and how to prototype during mechatronic design projects.

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