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Creating Dynamic Requirements Through Iteratively Prototyping Critical Functionalities

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Abstract

This paper introduces the wayfaring model for requirement generation. Rather than pre-fixing requirements, we propose exploring unknown unknowns, and suggest finding and adapting the emerging set-based requirements while exploring. Fundamentally, as primary navigation tool towards final requirements, we propose to find and use critical functionalities iteratively, within interlaced knowledge domains. The model argument is based on two cases: The developments of a conceptual desktop plastic injection molder incl. control system, and the iterative prototyping of molds for a lightweight carbon fiber composite bike saddle. In both projects, the critical functionalities dominate the direction of the next prototype and consequently proven design specifications emerge.

Keywords: Critical Functionality; Prototyping; Case Study; Manufacturing; Abductive Learning; Emerging Requirements

1. Requirement exploration

Prototypes are a powerful tool in product development and can be interpreted in a variety of ways. While some industries might see a prototype as the last few stages before being ready for serial production, we present two case studies where we used *'prototypes to learn'*, as Leifer and Steinert [1] put it. In the early product development phase where the final specifications are not yet known, some 'future' problems are not yet on the radar, and are hence lacking a valid solution ('unknown unknowns') [2]. This pre-lean product development phase is crucial, as later changes to the design and to the requirements will create enormous costs [3]. In this paper we propose a method that helps finding these unknown unknowns when tackling the challenge of developing a completely new product where the problem definition and requirement specifications still contain many degrees of freedom. Once these requirements are established, one can rely on other methods, such as systems engineering and lean, where this proposed method could provide viable requirement inputs, as described in Haskins et al. [4].

1.1. Build to learn

Ulrich and Eppinger [5] give a broad definition of what a prototype is: *'An approximation of the product along one or more dimensions of interest'*. Along the lines of the d.school philosophy we see prototypes as *'anything that takes a physical form'* [6]. Elverum and Welo [7] point out that even for complex physical products where the costs of a prototype are high, it is even more important to understand how to prototype in an efficient manner in order to save money and still have highly valuable learning outcomes. Even quickly built, low-resolution prototypes can give the development team crucial information about potential shortcomings of their design early on in the design process [8,9]. Furthermore, different kinds of prototypes provoke different discussions within design teams [10]. However, they should be *'designed to answer questions'* [11]. We propose to use wayfaring in order to find the right questions and use the answers in the best way possible, namely to iteratively find and further refine requirements for the following development steps.

1.2. Wayfaring and probing a vision

Schrage [11] describes product development cultures in organizations as *'Spec-driven'* and *'Prototype-Driven'*, where in the first case the prototypes are designed according to predefined specifications, and in the latter case the specifications are constant subject to change under the influence of the various learnings from the prototypes. We see the prototype-driven development culture as a crucial element of the wayfaring model [12]. Similar to an explorer in the age of Columbus that sets sail in order to find new lands, a product development team departs to find the really big idea, and follows a vision and some vague and often imprecise or even wrong information (wayfaring). The opposing manufacturing analogy would be today´s cargo ship that create a steady just in time supply route over the oceans by following a pre-defined, optimized route to specific GPS locations (navigation). By prototyping and testing quickly and early on in the journey, the 'explorer' team can learn and consciously reflect on the outcome [13] and, unlike in pure 'trial and error', find new 'tracks' that nudges them in a promising direction towards the vision. Gerstenberg et al. [14] describe the process as follows: The journey consists of many probes, where each '*probe is a circle of designing, building and testing of an idea or prototype'*. In addition, they propose to prototype simultaneously in interlaced knowledge domains, creating multi-level probe-circles where each level represents one discipline involved in the development process. Fig. 1 and Fig. 2 graphically represent this process. Such iterative probing circles also increase the designers' confidence in their solution [8,9].

1.3. Critical functionality and functional requirements

Developing and refining a completely new product is – unlike in incremental product development – a long exploration of unknown unknowns and subsequent specifications. However, how can one find and create these requirements? During the wayfaring journey described above, one will deduct certain critical functionalities from the prototypes that need to be fulfilled in order to arrive at the really big idea. Especially in complex systems, these critical functionalities are often not foreseen since the solution is discovered along the way. By probing solutions for these critical functionalities we discover dynamic functional requirements, or evolving set-based requirements. Studies have emphasized the importance of the latter, as they do not constrain the future development, unlike when working with point-requirements [3,15]. The next prototyping iteration can then build onto the newly discovered functional requirement, until a satisfying solution is found.

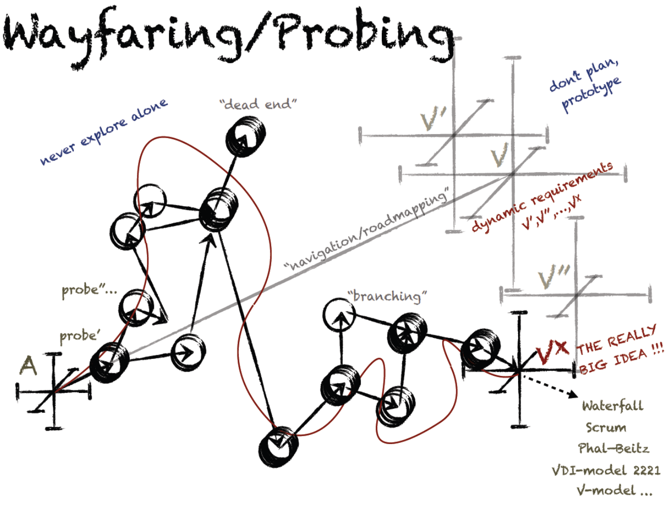

Fig. 1. The Wayfaring Process (From [14]).

Since it is not possible to map out all possible solutions to a complicated problem beforehand, there is no guarantee to arrive at the global optimum. However, through multiple probing cycles one can be confident that one will arrive at the best local optimum within the explored solution-space.

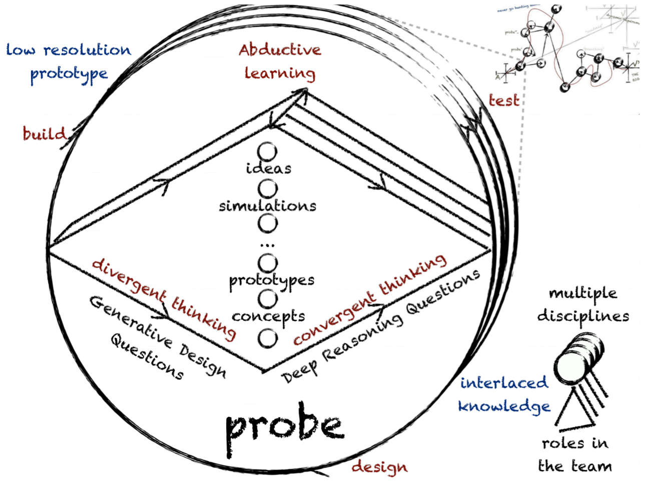

Fig. 2. Multi-Layer Probing Circle (From [14]).

1.4 Case studies

To support our proposition of using the wayfaring as a tool to discover critical functionalities and creating dynamic requirements, which in turn become dominant probing markers and design features, we analyze the following two case studies of development journeys: The development of a desktop injection molder, and the path to the first prototypes for a high-end carbon fiber bike saddle. In both projects, the direction shifted multiple times during the wayfaring process and critical functionalities that emerged along the way became the focus of intensive probing.

2. Case study: desktop plastic injection molder

2.1. Finding a need through wayfaring

Our first example is the development of a desktop sized plastic injection molder. The project started with a vision to improve the handover from CAD-models to injection-molded components in a major Scandinavian company. Because of expensive tooling, the design phase of injection molded plastic parts is critical. Moreover, if a component is designed poorly, and the tooling is manufactured accordingly, significant re-work is required on the tooling. This is both costly and can delay the product launch significantly.

The starting point for the project was initially to do finite element analysis (FEA) of plastic components to obtain knowledge of their structural integrity. However, after doing several rounds of probing, by testing both linear- and nonlinear approaches to FEA, as well as looking into the manufacturing process of injection molding, it became clear that FEA was too time consuming within the boundaries of the project. Therefore, we decided to shift our focus into prototyping.

The idea was now to explore different ways of prototyping injection molded components. We explored several techniques, such as additive manufacturing, indirect- and direct rapid tooling. Several of these techniques seemed very promising. However, a critical obstacle to overcome was to provide realistic mechanical properties in the prototype. From the prototyping techniques listed above, direct rapid tooling was the only technique that would provide these properties. In order to get a first feeling for whether or not we should proceed with this approach, we did a quick round of probing. By making polymer molds using a fused deposition modeling 3D-printer, and using a glue gun to simulate an injection molder. The question was to see if such a simple approach created any useful results.

After seeing that prototyping injection molded components using direct rapid tooling was within reach, we continued pursuing this path. However, a reoccurring problem was that there was no good way to test the various prototyping techniques, as this required full-scale injection molding machinery. Neither the company nor we had direct access to such infrastructure. Thus, we set off to build a simple injection-molding machine that could be used in a near-office situation. The according wayfaring journey is illustrated in Fig. 3.

2.2. Using critical functionality as navigation tools

The basic principles of injection molding are to melt a polymer, and then inject it into a cavity. We therefore continued our wayfaring journey by isolating the *critical functionalities*, namely heat and pressure, and probing them separately.

For pressure, we looked for inspiration in existing solutions, such as hydraulic clamps, full-scale injection molding machinery, and sealant guns. After probing several of these concepts, we learned that a purely mechanical solution would be suitable. The first requirement that emerged was therefore that the injection molder should be hand operated.

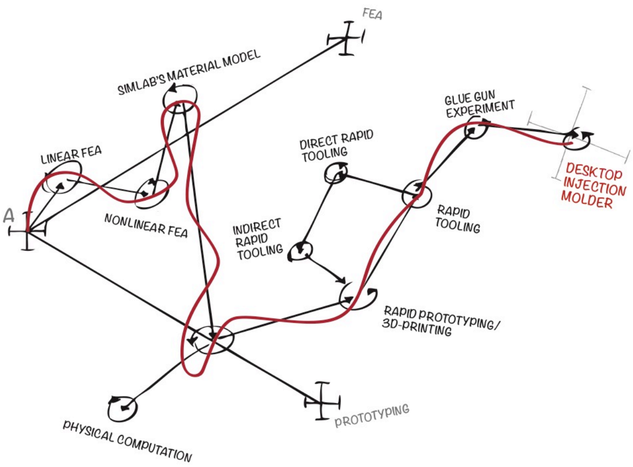

Fig. 3. The wayfaring journey leading up to the injection molder.

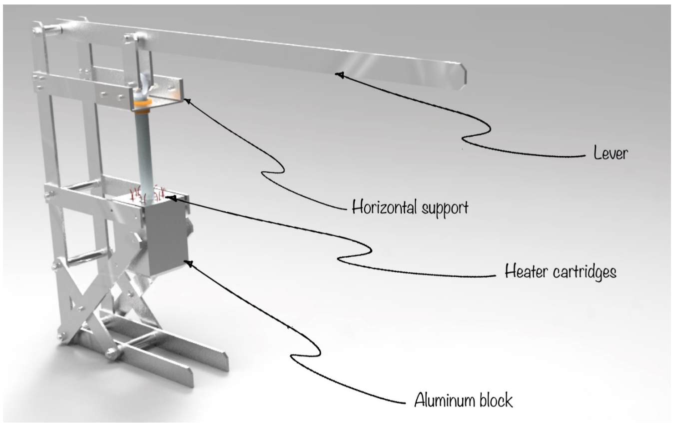

Fig. 4. CAD model of the mechanical structure.

The next round of probing consisted of sketching a cantilever-based design, and building a low-resolution cardboard prototype. Although at this point we only had one requirement, several more would emerge along the way. Because the injection molder had to be able to inject a minimum amount of volume, the height of the injection chamber, and consequently the minimum stroke, emerged. The prototype also showed the need for a horizontal support and a free link connected to the cantilever. Another advantage of the cardboard prototype was that it was easy to move around the pivot points in order to test various cantilever setups. Therefore, a smoothly working mechanism quickly emerged. A rough hand calculation of the theoretical maximum pressure provided by the current design gave a thumbs-up for moving on.

For heat, we considered stovetops, autoclaves and heater cartridges. However, seeing that some additive manufacturing technologies, such as fused deposition modeling, utilize heater cartridges to heat a nozzle, we identified that the same concept could be applied for the injection molder. Essentially, this meant heating a block of metal (in this case aluminum) by the means of heater cartridges. The requirements were therefore that the aluminum block had to fit multiple heater cartridges, serve as a heat medium, an injection chamber, and a nozzle.

2.3. Designing the details

Having found requirements for the critical functionalities, the remaining requirements and subsequent design emerged from what was available in terms of materials in the workshop and as well a few off-the-shelf components.

While physically building the structure, the CAD-model would serve as an interim reference (see Fig. 4). Consequently, if unknown unknowns were discovered while building, and changes had to be made to the design at this point, we would update the CAD-model accordingly.

2.4. Developing the heating system

Critical functionalities were also the main drivers for designing the heating system. This mechatronic system requires prototyping in three interlaced knowledge domains simultaneously, namely the software, electronic, and mechanical domains.

The three different sub-sections of critical functionalities are: Powering the heater cartridges; measuring the temperature; controlling the temperature. All sections were first prototyped independently and then combined with the other sections, in order to form a complete heating system.

For powering the heater cartridges, we used an Arduino Uno microcontroller and a breadboard. This combination allowed for probing several different circuit designs in a short period of time. The idea of our circuit design was to use a low voltage to control a transistor, which in turn controls a higher voltage. It took multiple probing circles of trying various bipolar junction transistors, metal-oxide-semiconductor field effect transistors and solid-state relays (SSR) before experiencing that an SSR was more robust and easier to use.

For measuring and subsequently controlling the temperature in the heater block, we used a k-type thermocouple. The code and circuit for the thermocouple was tested independently, before it was implemented together with the cartridge system. Finally, based on an open source proportional integral differential (PID) algorithm, the different software sections were combined to form a functioning controller.

2.5. Testing

The desktop sized injection molder was finally tested. Although the design had shortcomings, we managed to successfully injection mold simple test geometries. Some of the requirements that emerged along the journey and were tested are:

- The injection molder must be hand operated.
- The lever system must provide enough pressure to inject the polymer melt into the cavity.
- The heater cartridges must heat the aluminum block to at least 200°C.

The developed injection molder is currently being used in a research project investigating how to improve the handover between CAD-models, 3D printed prototypes and injection molded components.

3. Case study: carbon fiber bike saddle

3.1. Introduction

Our second example of employing the wayfaring model is the development of a novel solution for lightweight carbon fiber bicycle saddles. Traditional bike saddles are connected to seat posts in a way that requires a complex design, giving high stress concentration in the connection interfaces. This complex design makes the saddle heavy, and also more prone to failures. The project started with an idea of a new way of joining the saddle to the seat post, to overcome these shortcomings. For patentability reasons, the details of the actual design will not be disclosed here.

The critical obstacle to overcome in this project was to establish a good manufacturing method. Because of the critical functionalities, namely being light and strong, carbon fiber was an obvious material choice for the saddle. However, in order to reduce tooling cost while prototyping, low-resolution manufacturing methods were employed, namely using medium density fiber (MDF) molds for as long as possible. Along the journey, critical functionalities were used as the main navigation tool to allow dynamic functional requirements to emerge.

3.2. Building a proof-of-concept prototype

For obvious reasons, the joint between the saddle and the seat post had to be strong enough to support the weight of a human being. This was our first critical functionality. Before our initial design with respect to this critical functionality, we built a low-resolution prototype out of wood. From this prototype we could decide most requirements for the geometric shape of the joint. However, the prototype provided no information on how the design performed with respect to real life loads. We therefore decided to build a proof-of-concept prototype.

The aim of the next round of probing was to see how the design would perform when made from carbon fiber. We aimed at making the parts in the easiest and cheapest way possible to maintain pace, and have rapid learning cycles. Carbon fiber composite is the preferred material due to the ability to build lightweight structures. The unique thing about carbon fiber is the ability of tuning the material properties by adjusting the fiber orientation within each individual ply. Furthermore, carbon fiber pre-impregnated with epoxy (prepreg) was preferred because it is easier to handle in the manufacturing process when compared to dry fibers. The basic principle of manufacturing laminates is to cut and stack prepreg plies in a mold, and then apply heat and pressure to consolidate the laminate. The molds are usually made from metal, which provides a good surface finish. However, this also makes them expensive. Therefore, we decided to make the molds from a cheaper material.

Using CAD/ tools for modeling the geometry enabled us to CNC-mill the molds from MDF blank. After milling, we sealed the surface of the mold with epoxy, and then sanded it to a smooth finish, as this allowed for easier demolding of the saddle, as well as creating a good surface finish. The finished mold with the prepreg panels was then put in a sealed bag and a vacuum pump was used to pull vacuum, thus compressing the laminate. Finally, an oven was used to add heat during the curing cycle.

The seat post was made using a different approach: We rolled plies of prepreg on a mandrel and firmly wrapped the layup with PET film. When heat was added the film shrank, thus compressing the laminate. The other parts required to assemble the saddle and seat tube were similarly made by compressing prepreg around 3D-printed ABS male molds, which were left within the finished part.

Testing the saddle revealed a lack of strength in the joint, and geometric requirements were further refined and implemented in the CAD model. However, we could clearly see that we were heading in the right direction to realize this product as a lightweight solution.

3.3. *Improving the design*

For the next iterations of prototyping the focus was to get user feedback on the saddle geometry and joint strength.

To keep the prototyping costs at a low level, we decided to stick to MDF molds. To eliminate the need for sanding thereof we further improved the tooling process by sealing the surface with epoxy before doing the fine milling. This way we could do the rough milling in a soft material, and get a hard surface to do the fine milling afterwards, leaving a high tolerance machined surface with limited need for sanding and polishing. This new approach to making molds successfully enabled for rapid testing of multiple geometries of the saddle in order to increase the rider's comfort.

However, at this point it became apparent that MDF releases fumes at the elevated temperatures during the curing cycle. Unfortunately, these fumes enter the vacuum pump where they condense and gradually damage the pump. Furthermore, heating of the mold is time consuming and inaccurate, as the heat has to be transferred by convection or radiation. Also, the porous nature of MDF, even when coated with epoxy, made it necessary to put the whole mold in a vacuum bag in order to compress it. Another drawback is the exothermal reaction that takes place in laminates due to the low thermal conductivity of MDF.

Despite these disadvantages, using MDF enabled us to test and optimize the saddle design in a cheap and fast way to a point where it satisfied our expectations.

3.4. *Transitioning to aluminum molds and heat control*

The focus for the next iterations was on the critical functionalities of the curing process, namely: Heat, pressure, and debulking of the prepreg. Now that the design of the saddle itself was according to the original vision, it made sense to invest in a high-end mold made of aluminum.

The high conductive heat transfer coefficient of aluminum allows for direct heating of the mold, by the means of heat cartridges, and subsequent precise temperature control. The curing cycle consists of three phases: Ramp up, curing, and ramp down of the temperature, and each phase has to be specifically set according to the prepreg used. An emerging requirement was therefore precise temperature control.

Although there are commercial temperature controllers available, making our own was faster and cheaper. Similar to the heating system for the injection molder described above, we used the Arduino platform to run a PID-controller in combination with an SSR. Adding a touch display allowed for easy tailoring of the curing cycle. Fig. 5 shows the heat controller connected to the aluminum saddle mold.

Also, the upgrade to the aluminum mold enabled us to simplify the vacuum process by using the flange of the molds as sealing points. From struggling with regular vacuum bagging material, we learned that silicone bladders provide a superior solution, since they allow for higher curing temperatures, and are reusable.

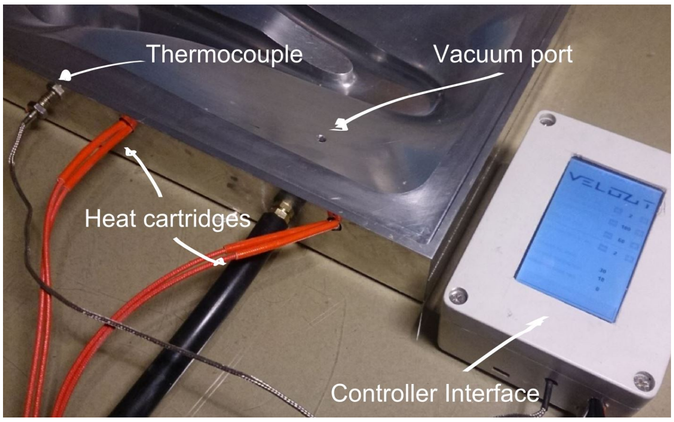

Fig. 5. Detailed view of heating system in the saddle mold.

While the overall quality of the parts increased as expected, it became clear that increased curing pressure was the next critical functionality that needed probing.

3.5. *Increasing curing pressure*

Prepregs are usually cured at high pressure assisted by an autoclave or by internal bladder inflation in order to reduce voids in the material.

For the first iterations of molding the seat post, we inflated a bicycle tube to achieve the internal pressure required to compress the laminate towards a female mold. From probing different bladder types, the functional requirements thereof emerged. It had to be flexible, and it had to be able to withstand up to 185°C. Silicone is a suitable material for this task. Using additive manufacturing and casting techniques, we were able to make the bladders according to the newly found requirements. Fig. 6 shows an illustration of the design and layup in a seat tube mold.

We realized that the same process can be utilized for the saddles: By clamping a lid on top of the mold, the silicone bladder, originally used to obtain vacuum, is supported by adding external pressure between the lid and the bladder (see Fig. 7).

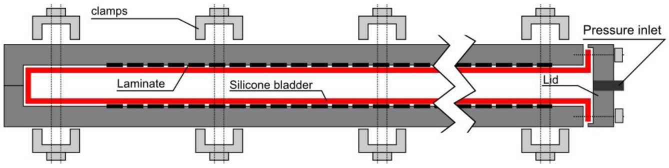

Fig. 6. Design and layup within the seat post mold.

3.6. *Summary*

This journey of prototyping critical functionalities has taken us from the initial concept idea to arrive at a final product that is adapted to a manufacturing process allowing for low tooling costs and low production costs compared to that of autoclave processed parts. Through iteratively prototyping critical functionalities, ever more specific requirements describing both the product itself and its manufacturing process have been continuously improved. Some of these were:

- The shape of both, the joint and the saddle itself.
- A high-end surface finish.
- Adjustable curing cycles for different prepreg configurations.

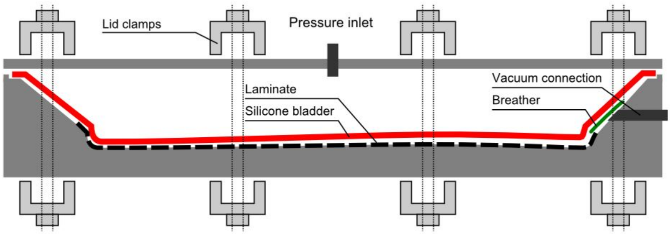

Fig. 7. Design and layup within the seat mold.

4. Closing remarks

We presented and analyzed two case studies of early stage product development processes that used the wayfaring method as a tool to discover critical functionalities and subsequent requirements. This approach helped in two fundamentally different projects: The desktop injection molder, where the external design was driven by the critical functionalities and the fulfillment thereof, and the bike saddle where the critical functionality had to fit in the external design that was predefined by standard dimensions for saddle and seat-post.

A benefit of employing the wayfaring model was the opportunity to discover *unknown unknowns,* for example the damaging nature of MDF molds, and adjust accordingly. This opportunity was primarily enabled by the probing loops of design-build-test. Of course intense simulation and external information gathering may have provided similar insights, but at significant higher costs esp. in terms of time and access/availability of expert information/services.

Furthermore, the iterative, repeating probing cycles allow for the emergence of prototype driven specifications, rather than specification driven prototypes. As pointed out by Schrage [11], are cultures in which prototypes determine specifications, such as in small entrepreneurial companies, more effective when information is scarce, and the outcome ambiguous. E.g. in the case of designing the electrical circuit with transistors instead of relays, testing was absolutely crucial for having a functional circuit. If the circuit had been designed without testing, a major design re-loop would have been inevitable.

Left unaddressed is the viability of this method within an industrial context, as this is part of ongoing research. However, empirical evidence, based on own experiences (e.g. Gerstenberg et al. [14]), and the engineering class ME310 that evolved into a hub for highly visionary industry projects [16], suggest that the iterative prototyping approach have a great potential within projects with high degrees of freedom.

One word of caution: It is unlikely that the wayfaring model as we applied it here provides similarly successful results when it comes to incremental later stage product-development, such as improving a certain product along the same critical functionalities, or when it comes to optimizing e.g. a production process. In these cases there are analysis and improvement tools available, such as lean, which fit a pre-defined solution space significantly better.

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