



**Sandia
National
Laboratories**

Accelerating Learning with Set-Based Concurrent Engineering

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March 2020

EXECUTIVE SUMMARY

The challenge: The Lithium Battery team knew using a traditional design-build-test approach to pack design would take too long to meet a major milestone. Previous instances of using traditional design led to late cycle design changes as testing revealed weaknesses that mandated changes to the design or increased acceptance of risk. Methods to eliminate the mechanical test failures earlier in the design process was necessary to reduce cost and schedule.

The approach: The Lithium Battery team (2500) and Business Excellence (10100) applied Set-Based Concurrent Engineering (SBCE), adapted for Sandia, to accelerate development time and capture knowledge for reuse. SBCE is a structured approach to product development, used in many industries, in which knowledge is created, re-used, and incorporated in a process of continuous learning to make better, more-informed decisions during the product realization process. SBCE begins by broadly considering sets of possible solutions and gradually narrowing down the set by determining and removing the least suitable option. The focus is on learning and capturing knowledge before design, development, or building takes place.

The payoff: With SBCE, the Lithium Battery team went from uncertainty about meeting schedule to significantly improving schedule. They will be ready for Baseline Design Review (BDR) much earlier than expected with better knowledge of the expected performance of their design space. SBCE allows for relatively easy changes to requirements within limits due to a better understanding of the performance envelope of which the design is capable. One of the major benefits of SBCE is that it captures knowledge for reuse. Not only does this benefit this project, but it benefits future projects that will not have to re-learn information that already exists. This supports the Nuclear Deterrence strategic objective to significantly reduce development cycle time.

This paper describes the thinking behind SBCE, how it's been applied to successful technological breakthroughs in history and how Sandia is using this method with lithium batteries to accelerate learning while decreasing product development time.

OVERVIEW OF SBCE

The traditional design approach for product development is to develop a design based on customer requirements and technical knowledge, build the product according to the detail requirements provided, and then test the product to validate that it works as intended. The team typically starts by identifying a single design approach and spends their time validating a single design during testing. Design teams often encounter issues in the course of development with performance, manufacturability, interfaces and more. To compensate for test failures, teams often build in time into the schedule for additional design loopbacks. Further, when the loopbacks lead to change, the late changes are costly and risky, causing the team to focus on “fixing the bare minimum” to meet cost and schedule expectations.

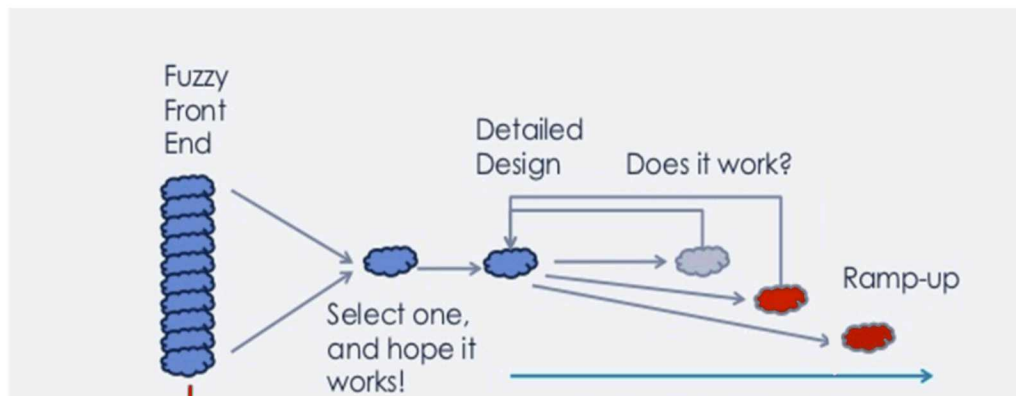


Figure 1: Traditional Serial Design Forces Early Decisions and Loopbacks [1]

Traditional serial design also comes with additional challenges. Design changes late in the design process are specific to one-off problems and unique designs, so the learnings are not applicable to future designs. Tight deadlines can lead to inadequate documentation of the solutions prohibiting knowledge transfer to future teams. There are also costs to other projects as staff are brought in to struggling teams to meet design deadlines. For team members this leads to fatigue, burnout, and job dissatisfaction. Worst of all, at the end of the design process, it is difficult to prove that the final design is the best design to satisfy the needs of the customer.

Set-based concurrent engineering provides an alternative approach that alleviates many of the challenges of traditional serial design. SBCE is named thusly because it begins with sets of possible solutions that meet user’s needs which are gradually narrowed down to converge on a final solution. The process to reduce the set of possibilities is completed by removing alternatives that are least likely to be successful, delaying the decision to determine the “best design” as much as possible. By casting a wide net for solution space, it is more likely that a better option is the one built and delivered. This approach is used across industry with wide success [2] [4] [5]. The differences between Figure 1 and Figure 2 graphically depict the difference between traditional design and SBCE.

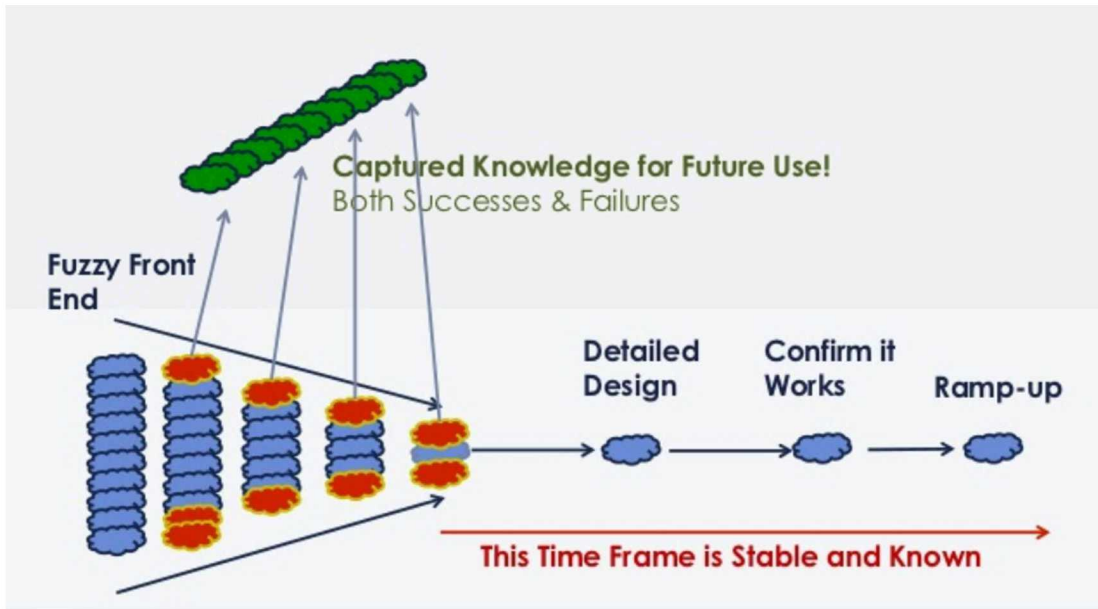


Figure 2: SBCE delays design decisions to reduce loopbacks while capturing knowledge [1]

The SBCE process allows convergence on a final solution by identifying and closing knowledge gaps. This leads to better, more-informed decisions during the realization process. When done well the SBCE process results in:

- Reduction in probability of late discoveries and loopbacks
- Designs that are more robust to requirements changes
- Effective knowledge capture and reuse
- Better characterized design space

The Business Excellence team has adapted SBCE for Sandia to include five elements that lead to convergence on an optimal design solution [3]. They are listed here and described in detail in for the Lithium Battery Project.

1. Map the design space
2. Identify and close knowledge gaps
3. Establish feasibility (technical and customer) before committing
4. Prototype, test and analyze
5. Capture knowledge throughout the process

FIRST IN FLIGHT THROUGH SBCE

To understand the theory of SBCE in an application setting, we can start with the story of the Wright Brothers and their quest to be first in manned, controlled, and powered flight– the airplane [2]. The journey to first flight was an intense global competition with opportunity for fame and fortune. The risks were unbelievably high including bankruptcy, injury and even death. History credits the Wright Brothers as first in flight – how did they get there?

The most important insight the Wright Brothers had was looking at the way their competition approached design. Others were spending thousands of hours designing and building. At the conclusion of all the effort, a few seconds were spent testing using the traditional design approach of design, build, test, repeat. The failed tests of the whole system, the airplane, often lead back to the design drawing board as it was not obvious what component of the system failed.

The Wright Brothers thought there was a better way. Before designing their plane, they decomposed the problem of flight into three critical functional areas of knowledge: lift, control, and propulsion by mapping the design space. They then identified and closed their knowledge gaps through experimentation early in the design process. This helped establish feasibility before committing to a final design.

The Wright Brothers systematically closed their knowledge gaps and applied their learnings to other knowledge gaps in their design. They prototyped, tested, and analyzed elements of their design to ensure their designs were converging. The Wright Brothers were able to prototype with hundreds of wing designs and catalog their learnings. As they approached the design needs for their propellers, they drew from the knowledge gained in wing design to accelerate their propeller design cycle because of the knowledge they captured throughout the process.

Not only did this methodology result in significantly reduced design costs in terms of time and money, but also, they were able to accomplish the design goal (Table 1). Their first airplane design flew without any modification.

Table 1: SBCE Led to Success on the First Flight [2]

	Other Inventors	Wright Brothers
Time invested	~17 years	~22 months over 4 years (designed & built full airplane only 6 months before they flew!)
Investment	~\$70,000	~\$1000
Approach	Design, Build, Test, Repeat	Test, Discover Knowledge Gaps, Design, Build
Result	Airplane never flew	1 st Design Successful

The Wright Brothers’ success shows the power of SBCE. It is a structured approach to product development in which knowledge gaps are identified and closed to make better, more-informed decisions during the realization process.

THE LITHIUM BATTERY APPROACH

Recognizing some of the same shortcomings of the traditional design cycle, the Lithium Battery team has embarked on their own application of SBCE. Their journey began in late 2018 and is expected to be completed in late summer 2020. Facing a tight design schedule, the Lithium Battery team began the SBCE process to address an issue with an environmental test failure. The team has worked its way through mapping the design space, identifying knowledge gaps and is in the process of knowledge gap closure and generating trade-off maps.

1. Map the Design Space: Causal Maps

The Lithium Battery team began their SBCE journey at a workshop where they mapped the design space as they knew it using customer requirements and technical knowledge. This stage of SBCE is intentionally vague to identify sets of possible designs. Figure 3 below shows the initial map of the design space for the lithium battery.

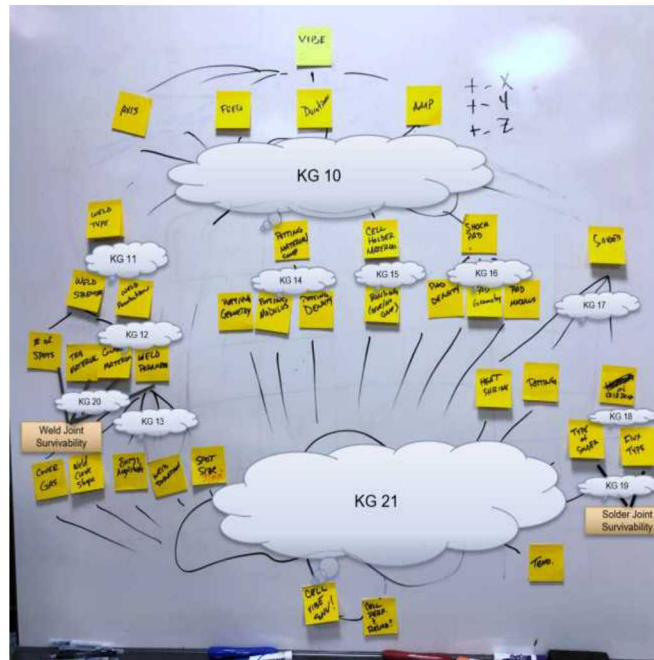


Figure 3: Initial Mapping Exercise from the Lithium Battery Workshop

A key element of mapping the design space is causal mapping to visually represent the relationship between each relevant decision. SBCE focuses on systematic exploration of capabilities from end-to-end throughout a system, subsystem, component, or subcomponent. Causal mapping links each decision through relationships to map the entire causal structure of the area of interest. This enables the greater system of interest to be broken down into smaller relationships that can be understood more simply, and at the same time more deeply. During the mapping process, each decision is mapped to the decisions that directly affect it.

2. Identify and Close Knowledge Gaps

The causal mapping process yields bits of information that are necessary to understand the relationships between decisions that are not fully understood. If the relationship is not understood, that leads to a knowledge gap. Knowledge gaps are forms of risk and are represented by clouds in the figure above. These knowledge gaps are the focus of subsequent design of experiments, simulation, and research. Additionally, getting a consistent set of names for design elements early in the process aligns what is meant by specific terms and exposes expert knowledge. For instance, it's okay not to know what an interaction looks like, it's not okay to pretend the interaction doesn't exist. A sampling of these knowledge gaps is contained in the next step.

Knowledge gaps can be closed through many methods such as research, simulation, or design of experiments. The closure of knowledge gaps equates to reduced risk, and reduced risk results in better designs. During this step the team is focused on learning more about the technical capability of the subject of interest. The data captured during mapping the design space and the plan to close knowledge gaps are used to satisfy the requirements of Conceptual Design Review (CDR), along with any early learnings gleaned from previous data or quick scoping experiments. Figure 4 is the same causal map, but much later in the process. Knowledge gaps have been closed and additional knowledge has been capture increasing the fidelity of the map.

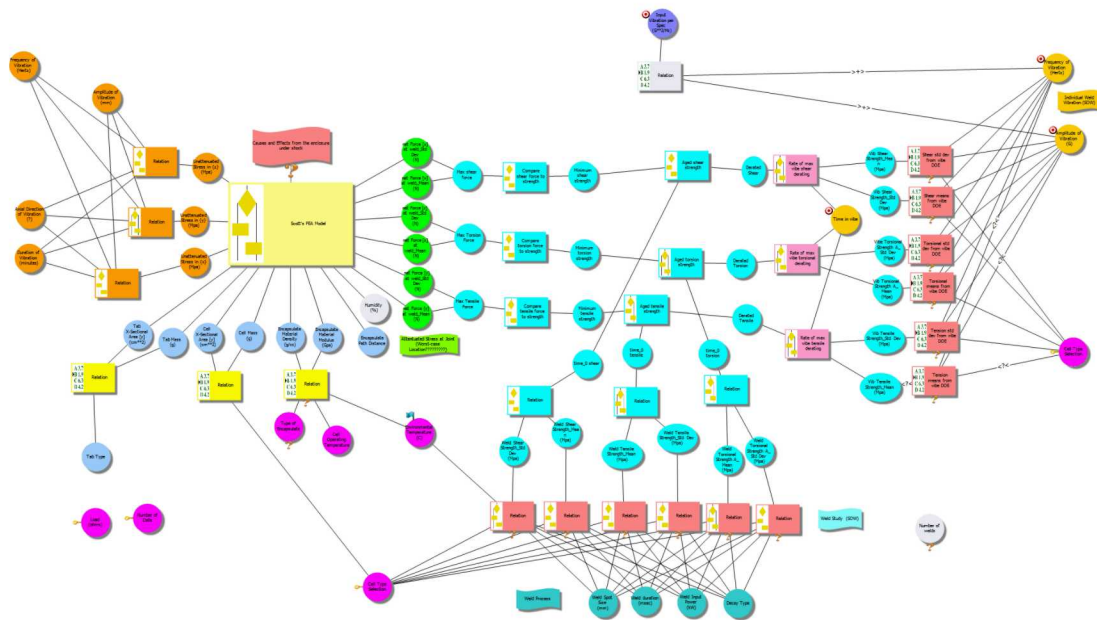


Figure 4: Lithium Battery causal map showing higher fidelity and closed knowledge gaps

It must be understood that at CDR, no design was presented for lithium battery. Instead, an array of option space, with trade-offs, was presented, with intent to educate stakeholders where limits may lie, and impacts of requirement changes may fall. This is different than the traditional approach as where a point solution in early stages is typically presented at CDR.

3. Establish Feasibility Before Committing

This step is about clarifying the design and validating it meets necessary parameters prior to deciding to narrow down the design sets. On lithium battery this will be done by modeling the design space and evaluating customer requirements.

- The design space can be modeled by preparation and translation of causal maps to trade-off maps. In this step the knowledge captured during knowledge elicitation and the data and trade-offs gained while closing knowledge gaps, transforms visual representations of mental models into computational models providing the insight to compare the total design space. The Lithium Battery team is starting to work their way through this process now.
- Customer requirements are then evaluated by overlaying the requirements onto the design space to show where we do and do not meet requirements. Here the margin becomes readily visible when considering the trade-offs that accompany customer requirements.

4. Prototype, Test, and Analyze

The Lithium Battery team has not yet entered this step but have laid the ground work. They will **build a full prototype** to test and verify the predicted failure rate through environmental testing. These tests will provide data to satisfy Baseline Design Review (BDR) requirements in the spring 2020. They will then **evaluate manufacturing** variability and impacts to performance from the model, in advance of Final Design Review (FDR) in mid-late summer 2020. **Final analysis** and the FDR of the pack design against the available design space, and predictions of yield and margin based upon the models.

5. Capture Knowledge Throughout the Process

The Lithium Battery team continuously captured knowledge through using a knowledge A3, or knowledge-brief, and causal maps in a software package called Success Assured™. This knowledge is readily available for future projects to use as they embark on their design process. Benefits of using the software include:

- Self-contained knowledge capture environment
- Translates from visual causal mapping to computational trade space
- Capturing files in native format
- Server hosted and available on the classified network, ensuring full knowledge sharing in a secure location
- Easy collaboration across teams
- Built in access control

KNOWLEDGE GAPS FOR LITHIUM BATTERY

One of the key enablers of SBCE is systematic identification, closure of knowledge gaps, and subsequent knowledge capture. The systematic identification and closure of knowledge gaps enables design teams to create the best possible design given relative trades-offs. Knowledge gaps are identified through causal mapping and represent risk. Knowledge capture enables future teams to significantly reduce the time to create a design by not having to relearn knowledge that has been created by a previous team.

Each of these knowledge gap identifications/closures/capture loops is an example of an accelerated cycle of learning. The team quickly identified what information or data was missing and then identified the plan to close the knowledge gaps. These smaller loops can be navigated more easily throughout the design cycle resulting in greater learning at a faster pace and lower cost.

The lithium battery team has identified many knowledge gaps throughout the process. Some were closed very easily through research of existing information or small-scale experiments, but others have been more difficult to resolve and take multiple cycles of learning. An example of small-scale experimentation, the Lithium Battery team used is seen with understanding shock impacts. Dozens of each type of battery were mounted and dropped at various orientations on a shock tower to understand the effect of shock and encapsulant behavior on battery performance. Instead of building a full prototype at a high cost, the team was able to gain deeper knowledge through small scale experimentation at a significantly lower cost. The knowledge gained was then used to influence future shock simulations to provide quicker turns on additional cycles of learning. **Table 2** shows some of the breakthrough knowledge gained as a result of identifying and closing knowledge gaps.

Table 2: Lithium Battery Knowledge Table

Knowledge Category	Knowledge Gap	Knowledge Gained
Shock	Interaction of shock and encapsulant on battery behavior	Battery shock behavior with encapsulants is markedly different than previously understood
Shock	The effects of various pack components on mechanical survivability	Pads in the battery pack serve the role of uncoupling the main pack from the mechanical insulation to the case
Shock	Effects of low frequency shock	Low frequency shock is not a concern
Weld	Repeatability of weld process	Tab weld process were not optimized
Thermal	Effects of encapsulant on self-heating	Encapsulants reduce effects of self-heating (not hurt it, as we had thought)
Reliability	The quantitative relationship between pack reliability and string count	TBD in future experiments
Shock	Quantitative effects of shock on battery failure rate	TBD in future experiments
Vibration	Effects of vibration on weld strength	TBD in future experiments

THE BENEFITS OF SBCE

The Wright Brothers, the Lithium Battery team and many others across time and different industries have experienced the benefits of SBCE as compared with traditional serial design. The focus that SBCE brings drives a thorough and systematic exploration of capabilities before down-selecting a design, further accelerating the cycles of learning. This enables engineers to understand the margin and associated trade-offs of various subcomponent, subsystem, and system interactions. Knowing where the boundaries of capability lie allows for more informed decisions when down-selecting a design, thereby avoiding potential problem areas in the design. SBCE captures the capabilities through causal maps, trade-off maps and visually displays the knowledge through trade-off charts. When this knowledge is displayed graphically, it becomes apparent to the designer where to select the optimal design. These capabilities of SBCE can be best captured in the following key benefits of the application.

- **SBCE reduces probability of late discoveries and loopbacks.**
Many designs suffer from late and costly discoveries including anything from margin changes to manufacturability. These discoveries can lead to late changes that are costly and can result in significant schedule delays. Knowledge gaps are closed in SBCE faster, at lower cost, and with higher fidelity because the system of interest has been broken down into smaller relationships. Each knowledge gap that is closed reduces the probability of late discoveries. The fewer late discoveries during a design frees engineers to invest more time in systematic exploration instead of troubleshooting.
- **SBCE designs are more robust to changes in requirements.**
SBCE invests time and energy into systematic exploration of capabilities early in the process resulting in a thorough understanding of the design space before down-selection of the final design. The design space is captured through causal and trade-off maps and display performance through solvers and trade-off charts. In many cases, the design trades necessary to open up requirement space are relatively straightforward and changes in requirements are easy to accept. This is because the necessary design space has already been mapped, studied, and its impacts understood. This contrasts with point design, where only that design has been verified to work and any design change requires, at a minimum, rebuilding and testing to the new requirement. This allows the requirements and design space to be flexible, much later into the design cycle with only minimal impacts, within the explored design space.
- **SBCE encourages the capture, sharing, and reuse of knowledge.**
Documentation can be an afterthought during design, particularly when schedule pressure is high. This is not the case with SBCE. SBCE systematically elicits and captures knowledge throughout the entire process. Knowledge capture is intrinsic to SBCE and is available for the team to continue to use throughout the current design and often into the next. Each closed knowledge gap results in new knowledge. This knowledge along with the knowledge captured through causal mapping is organized and stored for future teams. The next team has this information available to them, resulting in reduced time spent on the front-end investigating capability. Additionally, new team members can learn from the captured knowledge allowing them to become contributing members of the team significantly faster.

- **SBCE leads to better characterized design space.**

Closing knowledge gaps results in better knowledge and understanding of the system of interest. Systematically closing knowledge gaps reduces the risk of late and costly discoveries. The SBCE process includes visual representation of data and knowledge, making trade-offs readily apparent, facilitating a holistic conversation between designers, stakeholders, and customers. These factors lead to the most important benefit of SBCE: better designs. The design space, margin, and trade-offs are better understood allowing designers to select an optimal design with the minimum amount of risk.

The application of Set Based Concurrent Engineering has been proven to deliver these benefits both in an industrial setting for Wright Brothers and others, and within Sandia for the Lithium Battery team. The adoption of this methodology will aid in our ability to accelerate our learning cycles and decrease our product development time. All of which will be necessary for Sandia to deliver on its commitment to reduce the nuclear weapon design cycle.

LEARNING MORE AND GETTING STARTED IN YOUR AREA

For teams interested in application of SBCE methods, the first step is to define a manageably scoped system of interest. The key is to pick something useful but not overwhelming. This allows you to test the process in your specific area and knowledge gaps will quickly become apparent. With a smaller subsection, the design of experiments, modeling and / or simulation will be easier to execute to close knowledge gaps. Smaller experiments allow for more repetitions and replication resulting in greater data fidelity with less cost, increasing the confidence in the design.

In deciding where to start, consider areas such as:

- High known risk that is not well quantified. Identifying and closing knowledge gaps will reduce the risk profile.
- Lowest available margin in the design. A causal map will help you define the interactions of key parameters and can likely expose opportunity where margin can be gained.
- Interactions between components are not fully understood. The SBCE process of building a casual map and understanding trade-offs will bring new insights to the dependency of the components.

After selecting an appropriate system of interest, the team will draft a problem statement and scope. The problem statement serves to keep the team moving in the right direction. It should include background and context that will answer who, what, where, when, why, how, and how much. The scope will act as guard rails to keep the design effort inbounds.

The Laboratory Operating System team can also provide guidance on how to apply SBCE. Please contact us at los@sandia.gov or visit our website at los.sandia.gov.

ADDITIONAL RESOURCES

More information regarding SBCE can be found in the following books and referencing the bibliography

- **Lean Product and Process Development**
Allen C. Ward and Durward K Sobek II
- **Product Development for the Lean Enterprise**
Michael N. Kennedy
- **Ready, Set, Dominate**
Michael Kennedy, Kent Harmon, and Ed Minnok
- **Success is Assured**
Penny W. Cloft, Michael N. Kennedy, and Brian M. Kennedy
- **The Toyota Product Development System**
J. Morgan, J. Liker
- **Toyota's Principles of Set-Based Concurrent Engineering**
Durward K Sobek II; Allen C Ward; Jeffrey K Liker
Sloan Management Review; Winter 1999; 40, 2; ABI/INFORM Global pg. 67

References:

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- [2] P. Cloft, M. Kennedy, B. Kennedy; *Success is Assured*, Routledge, A Productivity Press Book, 2019, Print
- [3] D. Sobek II, A. Ward, J. Liker. "Toyota's Principles of Set-Based Concurrent Engineering", *MIT Sloan Management Review*, Volume 40, Number 2, Winter 1999
- [4] D. Raudberget, "Practical Applications of Set-Based Concurrent Engineering in Industry", *Journal of Mechanical Engineering*, Volume 56, 2010