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CIS SLIDE LOCK DESIGN PROCESS DEVELOPMENT

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Abstract

A process for the design of slide lock mechanisms for Central Industrial Supply was developed. The process incorporated tools from several theoretical design processes. The developed design process was tested using a case study, in which a self-closing mechanism was designed using the developed process. The case study proved the process to be effective, with the designed mechanism satisfying all requirements by 100% or more. Highlighted weaknesses of the process were afterwards corrected.

1 Introduction

Linear slide mechanisms are globally used to allow for extension of various devices, such as computer servers, from their racks. These mechanisms often contain locks, which prevent relative motion at predefined positions. Each slide mechanism contains three members and up to as many as six different locking mechanisms, thus making the design of linear slides a complex process. To simplify the design of these mechanisms a scientific design process was developed.

Central Industrial Supply (CIS) is an international supplier of linear slide mechanisms, as well as other mechanical devices. Different linear slides contain different locks to meet the customers' specifications. CIS is responsible for the design, testing, and production of a variety of slide lock mechanisms. The idea generation and selection stages of the design process are done through engineering experience alone, which is not the most efficient or the most reliable method. This project was aimed at developing a new design process for front locking mechanisms. The front locking mechanism, or mechanism that locks the slide in the fully extended position is difficult to design. For every customer it is necessary to design a different style locking mechanism to meet the customers' specifications. The specifications given by the customer are not all inclusive, so the design team must create additional requirements, to aid in the design process. This process relies on engineering experience alone, so it is not scientific, which makes it effective but unreliable. To improve the development of slide locks it was necessary to make the process more scientific.

"Over the last few decades the computer has been transforming the process of mechanism design from an art based largely on intuition and experience into a structured scientific discipline." [1] The process used at CIS, although effective, is not always reliable. CIS has outlined a general design process, which was documented as part of this project;

however a well-defined design process was developed, to replace the current method. The processes of redesigning and conceptual development in particular needed to be expanded, and made specific to CIS. A standardized scientific process was developed, which included steps for redesigning, as well as developing new locking mechanisms.

A design process was outlined and developed, which allows for reliable design and redesign of slide locks. The new design process clearly outlines conceptual development of slide locks and expands upon CIS's current design process. A case study demonstrated the effectiveness of the newly developed design process and used to optimize it. The design process will improve reliability, as well as reduce design concept development time.

The problem was clearly identified and defined using several different methods. Then, the new design process was developed that includes several methods and techniques for the design of slide lock mechanisms. Finally, the process was tested, for effectiveness and revisions to the process were made as needed.

1.1 Problem Statement

"The design of new slide locks at Central Industrial Supply relies on engineering experience rather than a standardized design process, which elongates the time that is needed to create a lock."

1.2 Goal Statement

"Develop a design methodology concentrating on conceptual design to improve the speed and reliability with which CIS is able to design slide lock mechanisms."

2 Background

To develop a knowledge base, significant amounts of background research on the theory of linear slide mechanisms and the principles of engineering kinematics were conducted. A profile of CIS was developed, outlining the company's growth and capabilities. The core of the investigation was in the field of engineering design. The variety of techniques for engineering design, principles of linear slides, kinematics and a profile of CIS are summarized in the proceeding chapter.

2.1 Linear Slide Mechanisms

Linear slide mechanisms are mechanisms designed for linear translation of objects within a cabinets or racks. The objects are typically computer servers or drawers. A typical linear slide is telescopic, with one or more of the members connected to each other with prismatic joint(s) (see [2]). The member connected with prismatic joints is seized with a locking mechanism at the maximum extension, thereby joining the two members as a single cantilever beam.

2.1.1 Members

A typical telescopic linear slide consists of three members: the cabinet member, the intermediary member and the chassis member.

Figure 1 below shows an illustration of the members.

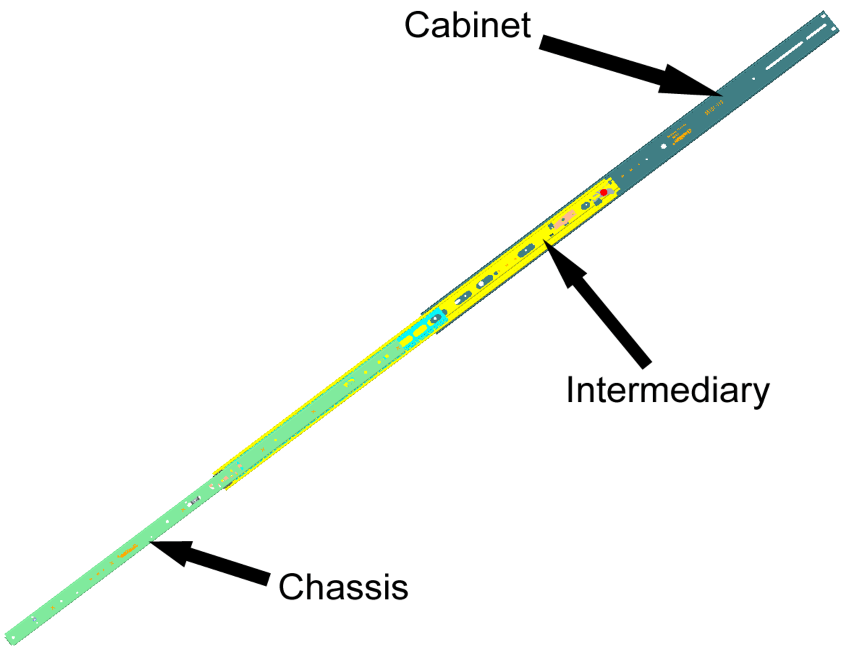

Fig. 1 Telescopic Slide Members
(from CIS slide 611-10190)

2.1.1.1 Cabinet

The cabinet member is the member of the slide that is attached to the rack, and normally does not move. This member supports the load, and applies the bending moment coupled moment to the intermediary and chassis members (when they are extended), and therefore this must be the largest and strongest member.

2.1.1.2 Intermediary

The intermediary member is the member of the slide that extends out of the cabinet member. When the intermediary member is fully extended, it locks to the cabinet member, and the chassis member starts being extended. Typically the intermediary extends no more than half the length of the member, to prevent large bending moments from being applied at its base.

2.1.1.3 Chassis

The chassis member is the member of the slide that extends out of the intermediary member when the intermediary member is fully extended out of the cabinet member. The chassis member is the member that the server is attached to, and thus it is the furthest member away from the rack. When the chassis member fully extends from the intermediary member it gets locked, and must be unlocked by the user to be retracted.

2.1.2 Slide Locking Mechanisms

A linear slide can have up to four different locking mechanisms, all of which serve different purpose. Those are the front locking mechanism, the rear lock, the staging lock and the disconnect mechanism. All of the locking mechanisms include the lock itself, and some also include a remote release mechanism, which the user has to interact with to release the lock. A typical lock consists of the housing, the housing for the locking element and the locking element. See Appendix A: Components for a complete list of terms related to slides and locking mechanisms.

2.1.2.1 Front Locking Mechanism

The front locking mechanism is the mechanism that locks the chassis and intermediary members together when the chassis member is fully extended, and lets the user manually release the lock. The front locking mechanism consists of a front lock and occasionally a front release mechanism. Appendix A: Components contains details on the components of the front locking mechanism. The project's goal was to develop a conceptual design methodology to improve the speed and reliability with which CIS is able to design front locking mechanisms.

2.1.2.2 Rear Lock

The rear lock is the mechanism that locks the intermediary and the cabinet members together when the intermediary member is fully extended out of the cabinet and the chassis is being extended. When the chassis member is retracted back into the intermediary it releases the rear lock.

2.1.2.3 Staging Lock

The staging lock is the mechanism that locks the chassis and intermediary member together when the intermediary member is not fully extended out of the cabinet. Once the intermediary member is fully extended out of the cabinet, the staging lock is released as the rear lock is locked, and when the chassis member is retracted into the intermediary member, the staging lock locks as the rear lock is released.

2.1.2.4 Disconnect Mechanism

On some slide designs there is a disconnect mechanism, which allows the user to completely pull the chassis member out of the intermediary. When both the intermediary and the chassis members are fully extended the user can activate the disconnect mechanism and pull the chassis completely out of the slide mechanism. The disconnect mechanism can only be released manually, by the user, manually.

2.1.2.5 Self-Closing Mechanism

Self-closing mechanisms operate under different principles from other locking mechanisms on the linear slides. A self-closing mechanism moves the chassis and intermediary members of the linear slide into complete retraction if the two are retracted to within a certain distance (usually 2” or less) to complete retraction. Other locking mechanisms prevent the motion of the slide members. However, the fundamental components and characteristics of the self-closing mechanism operates are the same as any other locking mechanism.

The important consideration in the design of self-closing mechanisms is the functional difference between the self-closing mechanism and other locking mechanisms. Structurally however, the self-closing mechanism are nearly identical to other locking mechanisms, which is why the same design process can be used to design all locking mechanisms.

2.2 Central Industrial Supply

According to [3], in 1955 Central Industrial Supplies (CIS) was founded in Texas, USA. Since then the company has grown into an international corporation. To date CIS has branches in the United States, Europe and Asia, with engineering and manufacturing being concentrated in Asia. See [4] for a complete description of CIS's product line. Large portions of the company's products are linear slides for server racks, and some of the customers include Dell Computers, Sun Microsystems and Hewlett-Packard.

2.2.1 History

In 1955 CIS was founded in Grand Prairie, Texas, USA, at the time a manufacturer of small mechanical devices. CIS grew and as did the market for the products it produced, and the company began marketing its products throughout North America. In 1996 the company became global and established a logistics service branch in Singapore. In 1998 CIS Grand Prairie, TX achieved ISO registration, and a year later CIS Houston, TX and Asia Pacific Central Industrial Supply (APCIS) Singapore also achieved the ISO registrations. The company continued to expand, establishing a large manufacturing facility in Wuxi, China in the year 2000. Appendix B: CIS's History contains a more detailed timeline of the company's history.

Figure 2 below shows the world map of CIS locations.

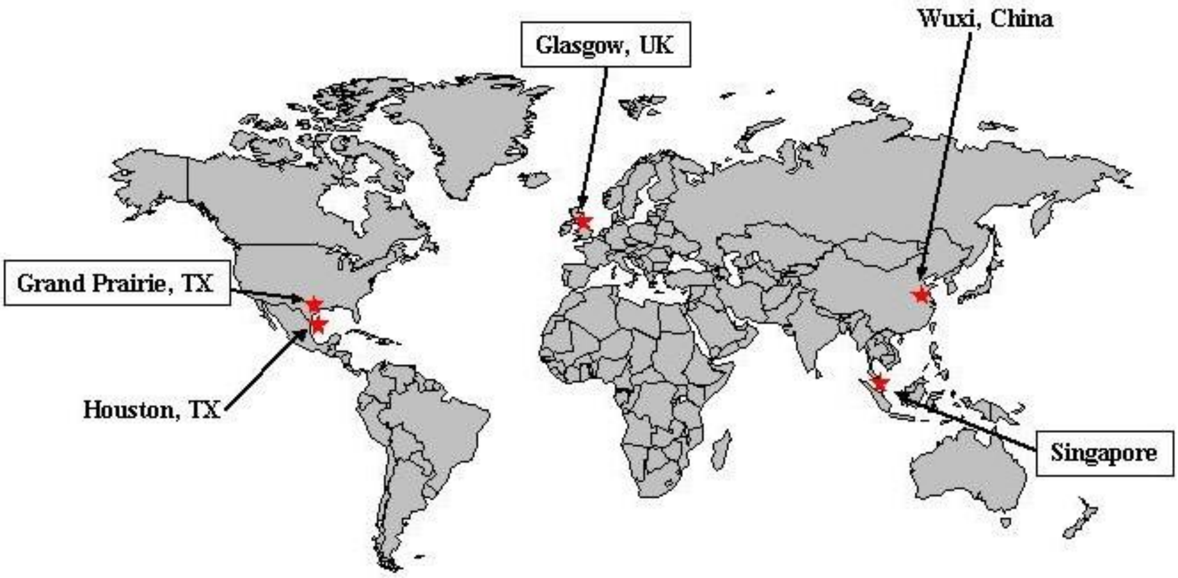

Fig. 2 CIS Offices Locations
(from [5])

2.2.2 Branch Locations

Currently CIS's branches in Grand Prairie, TX and Glasgow, UK, perform primarily logistical functions.

The company's engineering design, research and development branch is concentrated in Singapore. All conceptual design and analysis occur in Singapore, with most of the testing and prototyping occurring there as well. The Singapore office maintains a strong relationship with the Wuxi office, and a number of operations of the Wuxi office are overseen by the Singapore office engineers.

CIS's manufacturing branch is located in Wuxi, China. The manufacturing of the slides includes metal stamping, roll forming and assembly, all of which is done in the CIS facility. The Wuxi branch also contains facilities for machining parts, as well as the dies used in the rolling and stamping process. Electroplating the steel members and die-casting of the components of the locking mechanisms is done out of house.

2.2.3 Product Line

CIS's product line has evolved over the years. Currently, the company concentrates on designing and manufacturing linear slide mechanisms and cable management arms for managing servers on server racks. The slides are for a variety of customers, each with their own specific requirements for size, shape, strength and accessibility. To meet these needs CIS produces a variety of sliding mechanisms with a variety of locking mechanisms, mostly unique to each customer.

2.2.4 Current Locking Mechanism Design Process

Prior to this project, CIS design process for the locking mechanisms was generic, and could be summarized as the sequence of steps in Table 1:

Table 1 CIS's Current Locking Mechanism Design Process
(see Appendix C: Personal Communication with Al Barry, CEO of CIS)

1.	Simple feature requirement (e.g. lock slides when open, manual release to close)
2.	Concept (from engineer experience and sketches)
3.	Design Calculations (free body diagram and analysis of loads and forces
4.	Design solid model (Pro-E 3D model)
5.	Finite element analysis of critical areas (Pro-Mechanica)
6.	Prototypes and testing
7.	Manufacturing feasibility and cost
8.	Final design

This project expanded and standardized the first two steps of the design process, concentrating on the conceptual design step. Also, the whole process' shape was expanded into being more adaptive to the specific feature requirement.

2.3 Theory of Mechanical Design

Professor Norton of Worcester Polytechnic Institute [6] separates design of mechanisms into two principal components, synthesis of mechanisms and analysis of mechanisms. A relatively complete synthesis of a mechanism is necessary prior to conducting a kinematic or kinetic analysis. Several theoretical design methodologies exist to arrange the general procedures of synthesis and (normally) analysis into a more systematic approach. These methodologies typically are tailored for a specific application and thus using them requires modification.

This section addresses the theory of several important design processes as well as the two important approaches to analysis: kinematic theory, which also plays a significant role in synthesis of mechanisms and the Finite Element Analysis.

2.3.1 Theory of Design Engineering

The goal of a good design process is to provide a methodology for a reliable and effective design of mechanism solutions to real-world, unstructured engineering problems [6]. In the recent years, a great deal of research was conducted on expanding and standardizing design methodologies. There have also been many developments in the implementation of computers in the design process, from kinematic software to artificial intelligence algorithms for mechanism synthesis. Several of these methodologies were considered and are summarized in the following section.

2.3.1.1 Professor Norton's Process

Below is a summary of the design process suggested by Professor Norton of Worcester Polytechnic Institute in *Design of Machinery: an Introduction to the Synthesis and Analysis of Mechanisms and Machines* [7]. This process is iterative, in that the progress is normally made by making two steps forward and one (or more) step back, as necessary:

- Identification of need

This is the administrative statement of need, typically given by the boss or the client. General customer requirements are included in this stage; however, this stage does not provide a structured, detailed problem statement. An example of such a statement is: "Design a better lawn mower."

- Background research

This stage is most often overlooked [8]. It involves looking at patent literature, previous solutions to a similar problem, and related technical publications. It must be understood that without a clear understanding of the need it is impossible to complete this stage, so the first two stages are commonly combined to some extent.

- Goal statement

This stage is the generation of a coherent goal statement, which is the outcome of the original goal statement and looking into existing solutions to similar problems. The outcome of this stage is a coherent goal statement and usually a coherent problem statement as well. An example of such a goal statement is: "Design a means to shorten grass."

- Performance specifications

This stage is the generation of a set of performance specifications, which describe exactly what the system must do. This is different from design specifications which describe how the system must do it, and are generated as part of the next stage.

- Ideation and Invention

This stage is the most difficult of the steps in this process. It consists of generating various conceptual ideas about how the system must meet the goal statement and the performance specifications. This process may involve brainstorming if working in a group or drawing analogies to other energy domains, it may also include using synonyms to describe the function of the system to be designed; inversion of the goal statement may also help. These are suggestions to this step; see section 2.3.1.4 below for more information on concept generation. This stage can be referred to as the "*Conceptual Design* stage". Notice, that including previously designed solutions discovered in the background research stage is an essential part of this stage, as often it is not necessary to generate new idea to solve a problem.

- Analysis

Analysis stage implies analyzing the quality and applicability of the ideas generated in the ideation and invention stage so that the best one could be picked. This stage may involve generation of some performance criteria to analyze the ideas (such as how scalable a design is, how manufacturable it is compared to other designs in question), as well as deciding which performance criteria are the most important ones, as no design is ever flawless and compromises have to be made.

- Selection

After the analysis has been completed, the best one has to be picked for further analysis. A common tool in doing so is the *Decision Matrix*; see Table 2 below for an illustration of a sample:

Table 2 Sample Decision Matrix

	Weight	Design Concept 1	Design Concept 2	Design Concept 3
Performance Criterion 1	3	2	5	4
Performance Criterion 2	1	4	2	1
Performance Criterion 3	2	5	3	1
Outcome		20	23	15

It is important to realize that the real advantage of the decision matrix is not the opportunity to blindly use the design concept with the highest outcome number, but rather the necessity to think about the priority of the performance criteria and the conscious separation of the design concepts (ideas may blend together as the outcome of the ideation stage).

- Detailed Design

This stage is the most mathematically intensive one. Normally, exact synthesis, solid modeling and finite element analysis are done at this stage. The intended outcome of this stage is the manufacturable design of a prototype. Sections 2.3.2 and 2.3.3 contain more detailed information on this stage. It is possible that the idea picked above does not work because of a unique mathematical principle or something similar, and so often from this stage iteration is required.

- Prototyping and Testing

This stage consists of manufacturing a prototype of the mechanism developed in the detailed design stage, and testing how well it satisfies the performance specifications developed in the performance specifications stage.

- Production

The last stage is normally conducted by the manufacturing engineering team instead of the design team, and involves developing the production line for an inexpensive and reliable manufacture and assembly of the developed design.

It must be noted that Professor Norton's design process, while effective, is also very general, and thus significant modification to most steps of the process were required. The process developed incorporated Professor Norton's design process into a more specific process fit for front release locking mechanisms.

2.3.1.2 Theory of Rapid Redesign

An idea not mentioned in section 2.3.1.1 above is that of *rapid redesign*. The approach to rapid redesign of Decomposition Patterns (later in this paper denoted as "*rapid redesign*") – is an approach suggested by Professor Simon Li and of University of New

Brunswick, CA and Dr. Li Chen of United Technologies Research Center, CT, USA in several papers [9-11].

Rapid redesign uses the notion of a *Design Dependency Matrix* (later in this paper denoted as "DDM"); see Fig. 3 below:

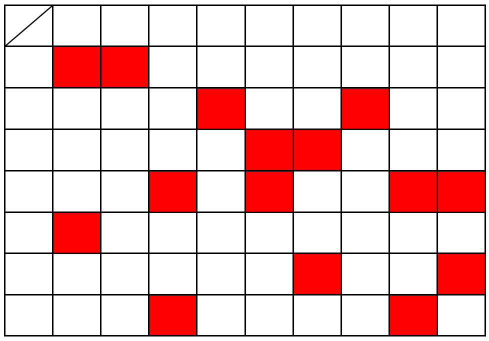

Fig. 3 Sample Design Dependency Matrix (DDM)
(adapted from [10])

In a DDM, each column represents a *design parameter*, and each row represents a *performance parameter* (Li [10] calls the rows "*design functions*"). A design parameter is a parameter that describes the structure of a mechanism. Similarly, a performance parameter is a parameter that describes the function of the design and how well the design satisfies the function.

The DDM is a binary matrix – it only contains information about dependency between the mechanism's design and performance parameters, denoted by the different color squares in Fig. 3 above. A shaded element indicates that the design parameter depends on the performance parameter, and a blank element indicates that the two are independent. Use of DDM can be complicated, but for the purposes of this project rapid redesign using DDM can be simplified.

The first step in the general process is defining the design parameters that describe the structure of the mechanism (Ref. [10]). These can be both qualitative and quantitative, but the key attribute of an appropriate design parameter is that the parameter is independent and not a function of other design parameters. The second step is defining the performance parameters that describe the mechanism's function. These can also be both qualitative and quantitative, but the key attribute of an appropriate performance parameter is that it has to refer to the customer specifications.

The third step is to fill in the DDM, indicating which design parameters are dependant on which performance parameters. Typically, several design parameters affect any given performance parameter. Proper descriptive definitions of design and performance parameters are very important (Ref. [10]).

After the DDM is defined it needs to be *decomposed* (Ref. [10]). The purpose of decomposition is to turn the DDM into a diagonal, or (more often), banded-matrix. Fig. 4 below illustrates a sample banded matrix, which resulted from the decomposition of the sample DDM in Fig. 3 above. The purpose of the decomposition is to divide the problem into autonomous (Fig. 4 below) or nearly autonomous blocks (Ref. [10]).

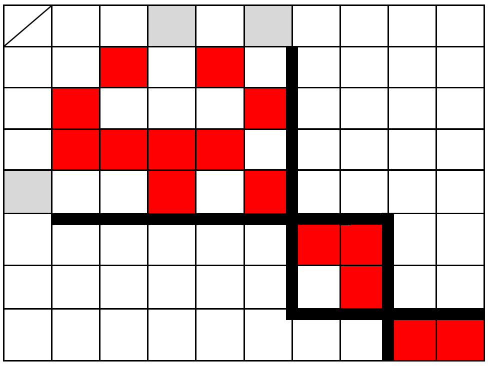

Fig. 4 Sample Banded Matrix
(adapted from [10])

The fifth step is to identify which performance parameter or parameters do not satisfy current requirements, meaning the parameters are faulty ([10]). The row or rows that correspond to the faulty performance parameter are highlighted. The column, or columns that correspond to the design parameters, which relate to the faulty performance parameter are highlighted as well (Fig. 4 above).

The sixth step is to fix the performance parameter's native block, in a predefined order using a complicated algorithm; in a non-autonomous matrix the adjoining block may need to be fixed as well.

The purpose of the rapid redesign approach is its use as an organizational tool. It does not identify the nature of changes to be made to the design parameters. Rapid redesign identifies the optimal order of making the changes to the design, thus making the redesign process as efficient as possible.

2.3.1.3 Value Engineering

Value Engineering is a process developed by Lawrence D. Miles, to decrease cost and improve performance for an existing product [12]. An advanced approach to value engineering is called Function Analysis System Technique (FAST), which asks three logical questions: "How is the function accomplished?", "Why is the function performed?", "When is the function performed?" [13]. This method for redesigning mechanisms develops a flowchart consisting of the answers to the three logical questions. The flowchart is analyzed and a *critical path* is generated, which allows for the association of function with various components of the mechanism. Then, the resulting flowchart can be analyzed to reduce cost and increase productivity.

2.3.1.4 Mental Iteration

To develop a complete understanding of the conceptual engineering process it is necessary to understand the mental iteration that goes into every new design. The mental iteration process is broken down into four distinct steps: analyze problem, generate, compose, evaluate [14]. In designing, engineers will go through much iteration of those steps, and more experienced engineers tend to go through more iteration. There are both benefits and drawbacks to mental iteration. Generally, more iterations leads to a less novel idea generated, however, it is also more reliable [14].

2.3.1.5 Parsing Design Specifications

To guide the creation of a conceptual design, a series of specifications is generated. "Design specifications with various natures can be identified and classified into three coherent categories: functional requirements, structural requirements, and design constraints." [15] Functional requirements define the motion that the mechanism must achieve, structural requirements define the loads the mechanism must withstand, and design constraints are usually customer requirements, such as aesthetics. This technique is used to simplify the design task for the engineer, by defining the kinematic chains only in terms of the functional requirements. Once a series of concepts has been generated, they can be eliminated by then taking into account structural requirements and design constraints. The shortcoming of this method is that many of the initial concepts generated are infeasible.

2.3.2 Kinematic Theory

Kinematics is the fundamental branch of mechanical engineering involved in designing mechanisms. This branch of dynamics of mechanisms involves only motion analysis, which excludes the forces generated by the motion. Kinematic synthesis constitutes several important decisions made about the mechanism's structure: number of links in the mechanism, the types of joints in the mechanism, the number of degrees of freedom in the mechanism and the ground link of the mechanism.

Coupler curve is the path one of the points on one of the links of the mechanism (called coupler point and coupler link, respectively) during the mechanism's operation. An important consideration is the Grashof condition of the mechanism, which simply states whether or not the coupler curve of the path is of closed form or not. For a fourbar linkage (a planar one degree of freedom mechanism consisting of four pin-jointed links) this can be determined using a formula involving the lengths of the links. It is assumed that the most basic complete mechanism in kinematics is a fourbar linkage.

A kinematic chain is an assemblage of links and joints interconnected in a way to provide a controlled output motion in response to a supplied input motion. A mechanism is a kinematic chain in which at least one link has been grounded (from Ref. [16]). Two types of joints exist: a form-closed joint and a force-closed joint. A form-closed joint is closed by its geometry – such as a pin in a slot. A force-closed joint is kept together by force provided by gravity, spring or other – such as roll-slide joint in a cam-follower (from Ref. [16]).

Kinematic synthesis can be subdivided into two major steps – type synthesis and dimensional synthesis (adapted from Ref. [1]). Type synthesis determines the number of links in the mechanism, their order (the number of joints on each link), the number of degrees of freedom in the mechanism and the type of joints in the mechanism. Dimensional synthesis determines the lengths of the links.

2.3.2.1 Graphical Synthesis

The process of three-position synthesis with specified fixed pivots is simple and requires basic tools, however it is an indispensable tool for the creation of pin-jointed fourbar linkages, without the use of a computer. Given the location of ground points and three positions that the linkage should traverse it is possible to quickly generate a mechanism which will intersect those points. Required tools are: a straight edge, a compass, and a pencil. It is possible to use the link lengths generated for further modeling and analysis.

Ref. [17] contains the description of the three-position synthesis with specified fixed pivots above, as well as other graphical synthesis procedures. Also, the program FOURBAR (Ref. [18]) by Professor Norton or a coupler curve atlas can be used for generation of the link lengths for a pin-jointed fourbar linkage.

2.3.2.2 Linkage Transformations

A linkage transformation transforms the type of the linkage, thus potentially changing the order of joints, the type of joints and the number of links in the linkage, while retaining the number of degrees of freedom. There is no set procedure to follow while transforming a linkage, however, Norton [19] outlines six rules for linkage transformations:

1. Revolute joints in any loop can be replaced by prismatic joints with no change in DOF of the mechanism, provided that at least two revolute joints remain in the loop. If all revolute joints in a fourbar linkage are replaced by prismatic joints, the result will be a two-DOF assembly.
2. Any full joint can be replaced by a half joint, but this will increase the DOF by one.
3. Removal of a link will reduce the DOF by one.
4. The combination of rules 2 and 3 above will keep the original DOF unchanged.
5. Any ternary or higher-order link can be partially “shrunk” to a lower-order link by coalescing nodes. This will create a multiple joint but will not change the DOF of the mechanism.
6. Complete shrinkage of a higher-order link is equivalent to its removal. A multiple joint will be created, and the DOF will be reduced.

Half joints referred to in the rules above are any joints other than revolute (pin), prismatic (slider), helical, cylindrical, spherical and planar joints. For example, a slot-follower (pin in slot) joint is a half joint with two degrees of freedom, very common in locking mechanisms.

Linkage transformations, among other uses, can be used to transform a fully pin-jointed linkage into a more complicated planar mechanism.

2.3.2.3 Software Packages for Kinematic Synthesis

A variety of software packages have been developed to aid the process of kinematic synthesis. Programs such as Working Model 2D (Ref. [20]) allow the engineer to create and simulate planar mechanisms with numerous degrees of freedom, and various orders of links and types of joints. There are two advantages to similar software packages over paper drawings of mechanisms. The first advantage is the ability to animate the desired mechanism. The second is the speed at which it is possible to reiterate and modify design concepts.

2.3.3 Computer-Aided Design

Three-dimensional computer models of parts, also known as solid models, are a necessary outcome of a design process. There exist several different software packages for solid modeling of parts. PTC Pro/ENGINEER (Ref. [21]) is used by CIS and was used in this project. It allows the engineer to model three-dimensional parts and includes plug-in modules for assembly and mechanism modeling as well as animation capabilities. PTC Pro/ENGINEER is compatible with PTC Pro/MECHANICA (Ref. [21]) for finite element analysis (FEA).

FEA and solid modeling software packages, as well as solid modeling, are fairly new but very important tools in mechanical design. A true solid modeling package allows the engineer to mathematically define the geometry of a part, or an entire mechanism, in a format accessible to other software (like FEA or Computed-Aided Manufacturing, CAM packages). A true FEA package allows the user to "mesh" the part/mechanism into a lot of tiny but finite-sized elements and then conducting stress or deflection analyses on each individual part, thus identifying areas of stress concentration, locating design points and calculating the part's and/or mechanism's safety factors. Certain solid modeling and FEA software come in joined commercially available software packages, which include packages in the sections below. Pros and cons were taken from a personal interview with Professor Cobb of WPI [22]:

2.3.3.1 Pro/ENGINEER and Pro/MECHANICA

Published by PTC [21]. This is the CAD/FEA package used by CIS. It is a parametric-modeling CAD/CAM/CAE/FEA family of software packages. Pro/ENGINEER is the solid modeling package; Pro/MECHANICA is the corresponding FEA package.

- Pros: Easy to upgrade into more powerful software; modular package (need to only pay for modules that will be implemented), very broad range of capabilities. Somewhat more powerful than SolidWorks in terms of complicated geometric shape modeling and feature library. Solid models fully convertible into SolidWorks files although some complicated features may not be recognized by commercially available converters.
- Cons: Initially intended for non-Windows workstation computers and therefore is not as memory-efficient as SolidWorks, however, more powerful. Pro/MECHANICA's mesher will not automatically recognize geometric stress concentrations, and instead of remeshing the part and using more elements in the points of stress concentrations will increase the order of underlying differential equations, which is not always appropriate. This can be bypassed by manually increasing the number of elements upon recognizing that the part has stress concentrations.

2.3.3.2 SolidWorks and COSMOSWorks

Published by SolidWorks Inc [23]. SolidWorks and COSMOSWorks are also a parametric-modeling CAD/CAM/CAE/FEA family of software packages. SolidWorks is the solid modeling package, COSMOSWorks is the corresponding FEA package.

- Pros: Same as Pro/E's. Interface considered by many to be somewhat better than Pro/E's. Initially intended for Windows workstations and personal computers and therefore is more memory-efficient than Pro/ENGINEER. CAM capabilities similar to Pro/E package, G-code algorithms it produces generally require a lot less post-processing than Pro/E's G-codes. COSMOSWorks' mesher will automatically recognize stress concentrations. Solid models generated in SolidWorks are fully convertible into Pro/ENGINEER files, although some complicated features may not be recognized by commercially available converters.

- Cons: SolidWorks is not as powerful as Pro/ENGINEER, due to smaller feature libraries and difficulties with complicated shape modeling.

2.3.3.3 NX

Published by UGS [24]. NX was formerly known as Unigraphics. UGS NX is also a parametric-modeling CAD/CAM/CAE/FEA family of software packages.

- Pros: UGS NX is optimized for CAM.
- Cons: NX's FEA mesher utilizes fixed finite element shapes, which can be a severe problem for modeling complicated shapes, particularly holes drilled at an angle to the surface, surfaces with complicated curvatures and points with stress concentrations. The problem can be solved by greatly increasing the number of finite elements, which becomes unnecessarily computationally intensive. NX files cannot be converted to Pro/E or SolidWorks. Also a commercial license is very expensive.

There are also pure solid modeling and FEA packages available on the market, but those are very specialized and not fit for this project.

Computer-aided design allows for the development and testing of parts without any manufacturing. This analysis is theoretical and less than ideal, however, for rapid design and manufacturing CAD is an essential and necessary tool of ever-increasing importance.

2.4 Summary

The tools and methods outlined in the Background section above were utilized in the Methodology below to generate a new design process. Section 3 below outlines how this data was processed and utilized to develop and test a new design process.

3 Methodology

To achieve the development of a design methodology concentrating on conceptual design to improve the speed and reliability with which CIS is able to design slide lock mechanisms, three objectives were created. They are:

1. To identify the problem
2. To define a new design process
3. To analyze the new process

The methods used to achieve these objectives are outlined below.

3.1 Identify the Problem

The identification of the problem with the current design process was achieved using several different techniques. The initial understanding of CIS's design process came from the first e-mail communication with the project sponsor (see section 2.2.4 and Appendix C: Personal Communication with Al Barry, CEO of CIS). Through survey and personal communication, as well as research of theoretical design processes, the areas of the design process that needed improvement were identified.

3.1.1 Communication with Engineers

Presentations were given to the project group outlining the current process utilized at CIS and what improvements were needed. Also, an e-mail survey (see Appendix D: Design Process E-mail Survey Form) was conducted among the design engineers. The survey ascertained details concerning the current design process and any problems the engineers may have with the current process.

3.1.2 Theoretical Design Processes

To identify the shortcomings of the current design process it was important to research several theoretical design processes, so as to know ways in which to improve the process. Articles from ASME Journal of Mechanical Design were researched for specific approaches to mechanism synthesis and theory of design engineering. Professor Norton's Process (see section 2.3.1.1) was taken as the general guide to design process formulation. Several other articles were consulted as well.

The outcome of the methods for the first objective is in section 4 below.

3.2 Develop a New Design Process

After accomplishing the first objective it was decided that the primary focus of the new design process should be concept generation. The new design process was to focus heavily on conceptual synthesis and implementation of scientific tools and appropriate software for this step. Some iteration back to theoretical design process research was conducted, now focusing primarily on conceptual techniques for engineering design. Conceptual design software was researched providing several viable alternatives, and the optimal package was eventually picked based on a set of appropriate criteria. Afterwards, the new scientific design process was developed, presented as a flowchart with a detailed supplementary explanation of each step.

The outcome of the methods for the second objective is in section 5 below.

3.3 Analyze the New Process

To test and fine-tune the developed design process a case study was conducted. The case study split the project group into two teams, the experimental group and the observational group.

The experimental team implemented the new design process to design a new locking mechanism using mock customer requirements provided by CIS, keeping in mind that the quality of the final lock design was more important than following the process. The quality of the design itself was also measured quantitatively using performance parameters generated at the beginning of the process.

The observational team had several tools to assess the design process with. A second survey was developed for the experimental team, to determine the usefulness of the new design process as well as to identify flaws which may have been overlooked or unforeseen in the design process development. The observational team also had a checklist to follow the progress of the design team with, and note any design process steps skipped, or steps that required iteration.

Revisions to the process were made using the data collected from the data gathered over the course of the case study to improve the effectiveness and reliability of the new process.

The outcome of the methods for the third objective is in section 6 below.

4 Problem Identification

The initial understanding of CIS's design process came from e-mail communication with the project sponsor. Section 2.2.4 and Appendix C: Personal Communication with Al Barry, CEO of CIS contain details on the initial problem statement and the initial goal of the project.

From the personal communication it was concluded that the problem is generally in the problem statement and ideation steps of the process and that further investigation is required to identify the details of the problem.

4.1 Communication with Engineers

A presentation was given to the project team outlining the details of CIS's current design process. The presentation did not contain any significantly new information, and so an e-mail survey was distributed to CIS's design engineers, in an attempt to clarify the details of the problem. The form of the survey can be found in Appendix D: Design Process E-mail Survey Form. Three engineers responded; a sample response can be found in Appendix E: Design Process E-mail Survey Response.

From the e-mail survey it was concluded that the following issues should be addressed:

1. The problem definition step could use restructuring and specification.
2. No exhaustive background research is conducted during the design process.
3. The redesign of old mechanism is not always considered, and no standardized algorithm exists for a redesign.
4. The technical tools, such as software, used for conceptual design generation could be improved.
5. New concept generation stage should be standardized.

4.2 Theoretical Design Processes

A comprehensive background research on the theory of mechanical design processes was conducted. This was done to compare CIS's design process and its limitations compared to theoretical design processes suggested in mechanical design literature. Background section 2.3.1 contains a detailed summary of this step of the project.

After identifying the strengths and limitations of CIS's current process, the new design process could be developed, adapting the points and ideas from the theoretical design processes researched.

5 Developed Design Process

The design process developed for CIS consists of two main branches: redesign and new concept generation. Its primary steps were modeled after Professor Norton's design process (see section 2.3.1.1). The redesign branch of the design process was adapted from Professor Simon Li's and Dr. Li Chen's articles on decomposition-based rapid redesign (see section 2.3.1.2) as well as principles of value engineering (see section 2.3.1.3). The new concept branch of the process was designed specifically for CIS using transformation rules from Ref. [19] and the basic principles of mechanism synthesis and analysis (see section 2.3.2). Separating of functional and structural requirements was adapted from a research paper on parsing design specifications (see section 2.3.1.5).

This process assumes that the locking mechanism is a planar kinematic chain with a grounded link and exactly one degree of freedom. This is a good assumption because all locking mechanisms inspected fall under this definition.

Figure 5 below shows the outline of the general stages in the developed design process. Appendix F: Design Process Flowchart shows the detailed flowchart for the developed design process.

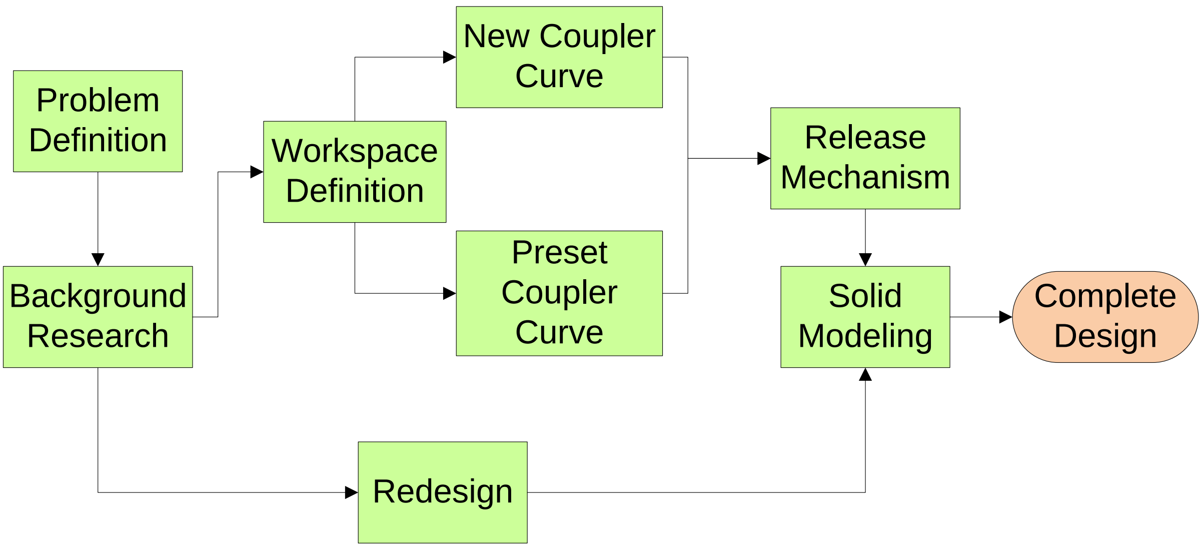

Fig. 5 Developed Design Process Outline

The design process consists of several general stages, with the most detailed stage being the Conceptual Design stage. The process is designed to be continuously iterative, however on the accompanying flowchart (see Appendix F: Design Process Flowchart) this is not explicitly stated. At any point in the process the engineer can reiterate to any of the previous steps as necessary.

It must be noted that terminology developed specifically for this design process is used extensively in this chapter, and the reader is advised to learn it prior to proceeding. Appendix A: Components and Appendix I: Database and DDM Terminology contain the developed terminology.

5.1 Identification of Problem and Goal

See Problem Definition, p. 70 for the flowchart of this stage.

In the first stage of the design process, the engineer identifies the problem, develops a goal statement and outlines the functional and structural requirements of the design.

5.1.1 Communication with the Customer

The design process starts with communication with the customer, by receiving an order from the customer. The customer's order is likely to be very broad and specify desired functions for all of the mechanisms in the slide, without stating which mechanism performs which function. From the customer's order the engineer has to develop a categorized list of functions, specifying the mechanisms that perform corresponding functions. From that categorized list the engineer can extract the customer's specifications for the locking mechanism to be designed.

5.1.2 Problem Statement with Specifications

From the customer's specifications for the mechanism to be designed the engineer has to develop a scientific problem statement. A well–structured problem statement will outline the problem the locking mechanism is supposed to solve using non–restrictive language.

Once the problem statement is made, the performance specifications are outlined. The performance specifications include two components: functional requirements and structural requirements.

Functional requirements consist of the consumer's specifications and quantitative engineering specifications.

Structural requirements consist of how much space the lock occupies and where along the length of the slide it can be located. These are determined by the design of the slide, which should be complete.

5.1.3 Goal Statement

After performance specifications are outlined, a goal statement can be generated. The goal statement will, in one sentence, describe the proposed final design. The goal statement, once created, can be used as a quick reference in the decision process at the idea generation step.

The creation of the goal statement completes the first major stage of the design process.

5.2 Background Research

See Background Research, p. 71 for the flowchart of this stage.

The second major stage of the design process is background research. The database with both current CIS designs and related patents (see Appendix G: Database) is intended to expedite this process. In CIS's case, the engineering specifications, the entire slide's design and relatively well-formulated customer specifications already exist. Therefore, the purpose of background research can be limited to checking for applicable patents and previous designs, and helping the ideation and invention stage. This approach may somewhat limit the creativity but is intended to speed up the design process.

The background research stage is separated into two major steps: inspection of the database for existing designs with similar performance specifications, and inspection of the database for patents with similar performance specifications. This stage is conducted early in the process primarily to saturate the engineer's mind with relevant ideas and let the subconscious generate the ideas by means of subconscious iterations (see section 2.3.1.4 for more information on the subject of mental iteration). Another point of the background research stage is to help (later in the process) test for whether or not any of the designs fully satisfy the performance specifications, or are prone to redesign.

5.3 Conceptual Design

The conceptual design stage is the most developed and most important stage in the design process. It includes several choices, so the engineer has to always be aware of the fact that the process is iterative and that if a previously made choice was incorrect the other choice should be investigated.

5.3.1 Previous Design Check

First the engineer has to check the database for any existing designs that may already satisfy the performance requirements – if there are such designs, then the engineer should use them, and the process is complete.

5.3.2 Proneness to Rapid Redesign Check

See Redesign, p. 72 for the flowchart of this stage.

Assuming such a design has not yet been developed, the next choice to be made is whether or not there are any locking mechanisms in the database prone to rapid redesign. A recommended indication of this is the following:

- A mechanism is prone to rapid redesign if only changes to the size of the elements or the type of release mechanism are required to make the locking mechanism satisfy the performance specifications.

- Any other mechanism is not prone to rapid redesign.

If there is a mechanism is prone to rapid redesign, the decomposition-based rapid redesign methodology (adapted from that described in section 2.3.1.2) must be applied. It is described in section 5.3.3 below. If there is not a mechanism prone to rapid redesign, a new concept must be developed. The new concept development is described in section 5.3.4 below.

5.3.3 Rapid Redesign

See Redesign, p. 72 for the flowchart of this stage.

The Design Dependency Matrix for locking mechanisms is required for applying the rapid redesign methodology. Such matrix has been developed and banded; see Appendix H: Design Dependency Matrix. The resulting banded matrix consists of two autonomous blocks, the blocks are presented separately in the Appendix.

The first step in the redesign process is to directly change only the design parameters that influence the faulty performance parameter. If there is more than one faulty performance parameter, new concept design is recommended.

The next step is readjust any of the design parameters that are responsible for the performance parameters that may have been affected by the changes made in the previous step. Ideally, this step will not be required. Some reiteration of the previous two steps can be applied to bring all of the performance parameters to be acceptable; if this does not happen, new concept design is recommended.

After all of the performance parameters have been fixed, the next step in the redesign process is implementation of the value engineering principles. This has been reduced to decreasing cost, by eliminating parts, and / or features, which do not contribute to the function of the mechanism. Upon completion of this step it is possible to move straight to

FEA and then prototyping and testing, therefore greatly increasing the speed at which it is possible to develop new concepts and ideas.

5.3.4 New Concept Development

If redesign and value engineering principles cannot be applied to generate a successful mechanism, then it is necessary to develop a new concept. Development of a new concept consists of several steps which occur prior to solid modeling. They are described in the following sections.

5.3.4.1 Location and Orientation

The first step in the development of a new concept is checking the functional and structural requirements for orientation. After doing so, the engineer must pick the location of the lock along the length of the slide.

This process assumes that all locks are planar mechanisms, which is a good assumption because a spatial mechanism would be unnecessarily complicated and is likely to occupy too much space. In a planar mechanism the relative motion between any of the parts and the ground occurs only in a given plane. The plane can be:

- Tangential – parallel to the walls of the rack and the server.
- Normal – perpendicular to the walls of the rack and the server.

After the location along the length of the slide is picked, the engineer must inspect both normal and tangential planes for potential interferences with the locking mechanism. The interferences are defined as features on the cabinet and the intermediary slide that can run into the lock (if designed without considering them) preventing the members' smooth relative motion.

After the inspection, the engineer must check whether or not structural requirements outlined in section 5.1.2 above allow for a design in the normal plane.

5.3.4.2 Workspace Definition

See Workspace Definition, p. 73 for the flowchart of this stage.

Based on the check, the engineer must define the workspace. The workspace is a planar drawing, easily drawn on a piece of paper. However, the optimal way to create the workspace is using a conceptual software package, in order to later use it to generate the mechanism. Several software packages were researched and compared over several criteria. A decision matrix to identify the optimal software package for CIS was constructed. The optimal software package was determined to be SAM 5.1 by Artas Engineering Software [25].

Table 3 below shows the constructed decision matrix.

Table 3 Conceptual Software Decision Matrix

Criterion	Weight	Software					
		Working Model [20]	SAM 5.1 [25]	Analytix/ Dynamix [26]	FOURBAR [18]	FIVEBAR [18]	SIXBAR [18]
Interface intuitiveness	2	9	9	2	5	5	5
Available Joint Definitions Quality	3	8	9	5	4	4	4
Available Shape Definitions Quality	3	10	9	5	3	3	3
Numerical Analysis Capability (coupler curves, graphs)	1	6	8	3	10	10	10
Cost rating (how acceptable the cost is for the company)	2	3	5	10	7	7	7
Total		84	90	57	55	55	55

The workspace illustrates three types of space: the space which is available to the locking element in any state (locked or unlocked, see Appendix A: Components for terms definitions), the space which is available to the locking element only in the locked state, and the state which is completely unavailable to the locking element.

If the structural requirements outlined in section 5.1.2 above allow for a design in the normal plane, the workspace must be oriented in the normal plane, since locks in the normal plane are simpler, as is indicated by the corresponding entries in the database. If not, the workspace must be oriented in the tangential plane.

After defining the orientation, the engineer checks the plane for potential interferences and denotes the spaces on the drawing or in software package.

5.3.4.3 Mechanism Synthesis

See Preset Coupler Curve, p. 74, New Coupler Curve, p. 75 and Release Mechanism, p. 76 for flowcharts describing the stages below. Conceptual software (Sam 5.1 [25] is recommended) will be very useful at this stage of the project.

This process assumes that the locking mechanism is a planar kinematic chain with a grounded link and exactly one degree of freedom. The planar kinematic chain assumption was explained in section 5.3.4.1 above, and the one degree of freedom restriction is reasonable because there is only one input motion (provided by the user) to the mechanism, and thus there must be only one output motion of the locking element. Therefore, the mechanism's synthesis is restricted to type synthesis and dimensional synthesis, which is the choice of the number of links and the types of joints of the mechanism and the determination of link lengths, respectively.

After the workspace is defined, the engineer has to decide whether or not a preset coupler curve for the locking element's motion in the workspace plane can satisfy the mechanism's functional requirements defined in section 5.1.2 above. This process identifies two preset coupler curves: a straight line and a circular arc. These coupler curves are treated separately because in all of the patents and existing designs in the database (see Appendix G:

Database) the locking element's coupler curve is either straight a circular arc, and thus these two curves are able to satisfy a majority of the functional requirements.

The process for using a preset coupler curve is defined in section 5.3.4.3.1 below. The process for using a new coupler curve is defined in section 5.3.4.3.2 below.

5.3.4.3.1 Preset Coupler Curve

If a preset coupler curve is being used, the engineer must first pick whether to use a straight or a circular arc coupler curve. When the curve is picked, the engineer should draw it on the drawing of the workspace, for easy reference. If a circular arc coupler curve is picked, the next step is identifying the location of the pin joint between the locking element and the ground, and the length of the rotating locking element link. If a straight coupler curve is picked, the next step is identifying the location and the length of the prismatic joint between the locking element and the ground.

This concludes the design of a lock with a preset coupler curve for the locking element; the next step is Release Mechanism Design, described in section 5.3.4.3.3 below.

5.3.4.3.2 New Coupler Curve

If a new coupler curve is being used, the engineer must first define three points on the drawing of the workspace. One point is the location of the coupler point when the lock is in the locked state, another point is the location of the coupler point when the lock is in the released state, and a third point is the location of the coupler point on the way from locked to unlocked state. The limitations of the workspace (what part of the workspace is available for what state) restrict where these points can be located.

When the three points are defined, graphical synthesis procedure (outlined in section 2.3.2.1) can be used to define a coupler curve for the coupler point on the locking element.

After the coupler curve is defined, a pin–jointed linkage can be defined to trace that coupler curve. The mechanism has one degree of freedom, so a fourbar or a sixbar pin-jointed linkage are going to be the most common linkages for tracing the coupler curves. The first linkage to try is a fourbar linkage, due to the fact that the precision of the coupler curve tracing is not important for the purposes of this mechanism.

After the pin-jointed linkage is defined, the transformation procedure can be applied to it. The point of the transformation procedure is to attempt to convert the mechanism from a pure pin-jointed linkage to a planar linkage with pin, prismatic, roller or half-joints. Details of the principles behind the transformation procedure are outlined in section 2.3.2.2. There is no general algorithm for when to use those principles to convert the link lengths of one type of linkage to another. However, the rules of linkage transformation are helpful for directing the brainstorm that occurs when the engineer tries to come up with a mechanism.

Another two types of transformations to consider are "living hinge" substitution and form-closed joint to force-closed joint and vice versa substitution. These substitutions do not affect the kinematic behavior of the mechanism, but can affect the cost. "Living hinges" can replace pin joints if both pin-jointed links experience no considerable stresses and can be made of plastic, thus making the two links one part. This substitution can make the linkage cheaper, but it only works if no considerable stresses are .

Figure 6 below shows a picture of a "living hinge". See section 2.3.2 for definitions of form-closed and force-closed joints.

Fig. 6 Living Hinge in Tic-Tac Container
(From [27])

The dimensions of the pin-jointed linkage generated cannot be unambiguously converted to a mechanism with multiple types of joints as described above. Rather, the transformation procedure is intended to use the dimensions of the pin-jointed linkage only as the design guide for a mechanism that could approximately trace the coupler curve. Also, since a fourbar linkage is already a very simple and manufacturable mechanism, it may be sufficient for the manufacturability required from the mechanism.

This concludes the design of a lock with a new coupler curve for the locking element; the next step is Release Mechanism Design, described in section 5.3.4.3.3 below.

5.3.4.3.3 Release Mechanism

See Release Mechanism, p. 76 for the flowchart describing this stage.

After the mechanism for tracing the locking element coupler curve is defined, the release mechanism can be designed. Release mechanism can be viewed as a separate mechanism that serves as the driver for the release of the lock. A procedure similar to the one described for the lock can be followed, with the coupler point this time being at the joint between one of the elements of the lock linkage and the coupler link of the connecting mechanism. The joint between the coupler link of the connecting mechanism and the lock linkage can be either a pin or a slot-follower. The driver for the release mechanism is an action by the user, possibly followed by a compliant element (spring), so alternatively, the engineer can choose the joint between ground and the link of the connecting mechanism that the user interacts with ("switch"). After the two joints are picked, the engineer only has to design a linkage between the two links two transform the user's input motion into the release motion of the lock mechanism. Notice, that the slot-follower joint between the release mechanism and the lock can be form-closed or force-closed. A force-closed joint will require a spring or gravity acting on the follower to keep the joint intact (at least while the release mechanism is acting).

5.4 Exact Shape Definition

See Solid Modeling, p. 77 for the flowchart describing this stage.

After the mechanism is synthesized, the exact shapes of each link (including the features of the ground that the lock is in contact with) can be determined. Generally, any link shape has to satisfy two criteria: not violate the geometric constraints of the locking mechanism, and resist the expected load with a preset safety factor. An initial determination of the shapes has to be made before the analysis for failure can be conducted, so the primary criterion at this step is the geometric constraints of the mechanism.

The outcome of this step is a set of solid models of all the elements of the mechanism. Section 2.3.3 contains a list of solid modeling software available on the market; Pro/E is recommended to CIS since CIS already has a license for it.

After the initial exact shapes of the mechanism components are defined, an FEA of the elements for failure can be conducted. Section 2.3.3 contains a list of FEA software available on the market; Pro/MECHANICA is recommended to CIS since it is adequate for CIS's needs.

If the FEA discovers that the solid models built fail under the applied loads, reiteration is necessary. If the factor of safety that the mechanism fails under is close to 1, then it may only be necessary to repeat the previous step in the process.

After the FEA verifies that the solid models are acceptable, the theoretical stage of the design is complete. After that prototyping, physical testing, and mass-manufacturing are possible.

6 Analysis

To develop a process which improved the speed and reliability of locking mechanism design at CIS a case study was conducted. The case study analyzed the design itself and the process as it was being completed. Revisions to the process were made as necessary according to the case study.

6.1 Self-Closing Mechanism

A self-closing mechanism was developed using the new process. Details of the developed design were not included in the report due to possible copyright issues, but the assessment of the design was. The quality of the design was rated according to pre-defined quantitative criteria, see Table 4 below. The quantitative criteria primarily focused on functionality of the design, and did not include cost. The final design satisfied all the quantitative criteria, so in that respect the process was proven valid for the design of self-closing mechanisms.

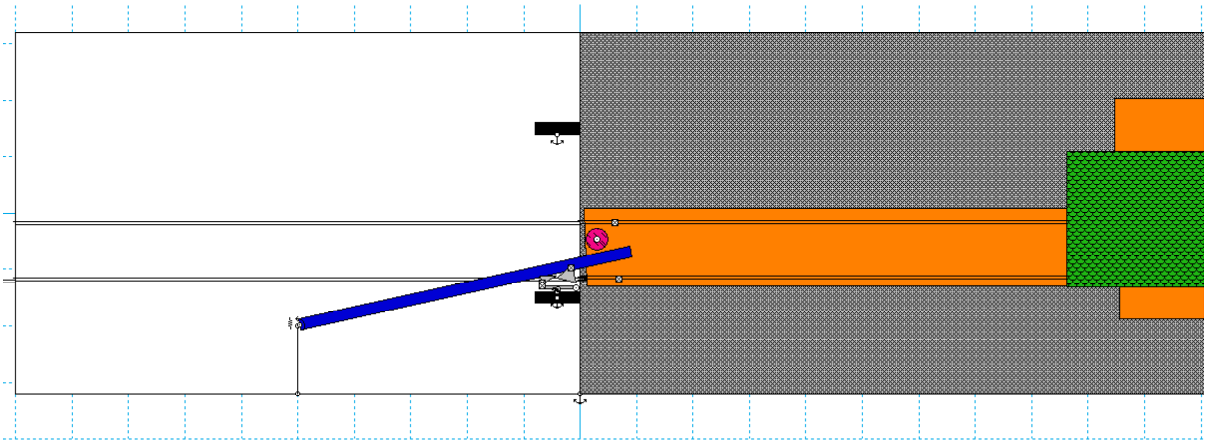

Fig. 7 Developed Self-Closing Mechanism Working Model Sketch

Figure 7 above shows a sketch of the lock of the self-closing mechanism developed during the case study. Working Model [20] was used to create the sketch.

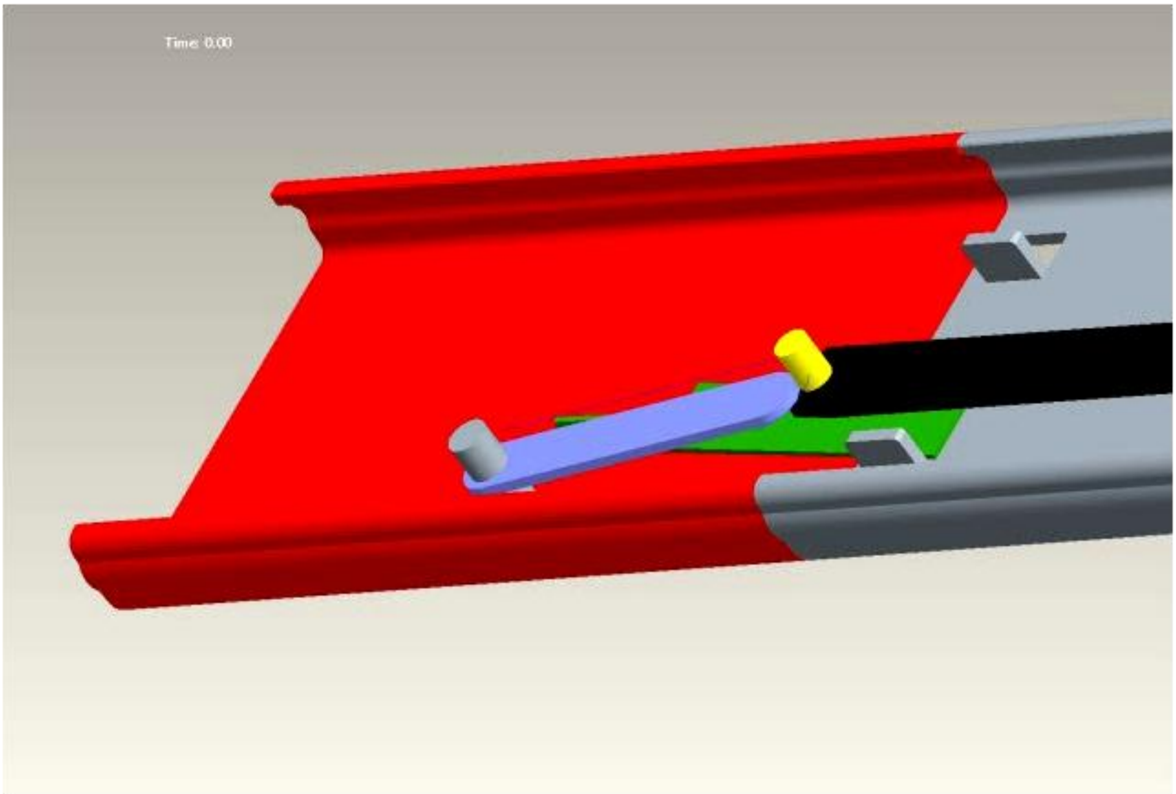

Fig. 8 Developed Self-Closing Mechanism Solid Model

Figure 8 above shows the solid model of the developed self-closing mechanism.

6.2 Process Evaluation

The primary purpose of the case study was to observe the design team, while it attempted to follow the process. From the observations as well as a survey given to the design engineers it became obvious that several changes were required to the current process, as several times the design team had to deviate from the steps provided, which were somewhat incomplete. Table 4 below shows the rating of the design produced in this case study based on the pre-determined functional and structural requirements.

Table 4 Self-Closing Mechanism Rating

Functional Requirement	Accomplished	Structural Requirement	Accomplished
Must fully retract intermediary and chassis into the cabinet.	100%	Height must be less than 39mm	100%
Retraction time < 5s	Retraction time = 2.5s	Width must be less than 8.5mm	100%
In the fully retracted position must apply force > static friction.	350%	Elongation < 10%	Elongation = 9.3%
Must engage with chassis being initially stationary.	100%		

6.3 Process Revisions

The primary revisions to the process were to clarify a few steps, and add steps. The definition of drivers was broken down into two separate steps. The largest addition to the process was the mention of software packages. The new flowchart notes when to use different software packages and how to use them. These software packages are crucial to the speed at which it is possible to develop new concepts and iterate.

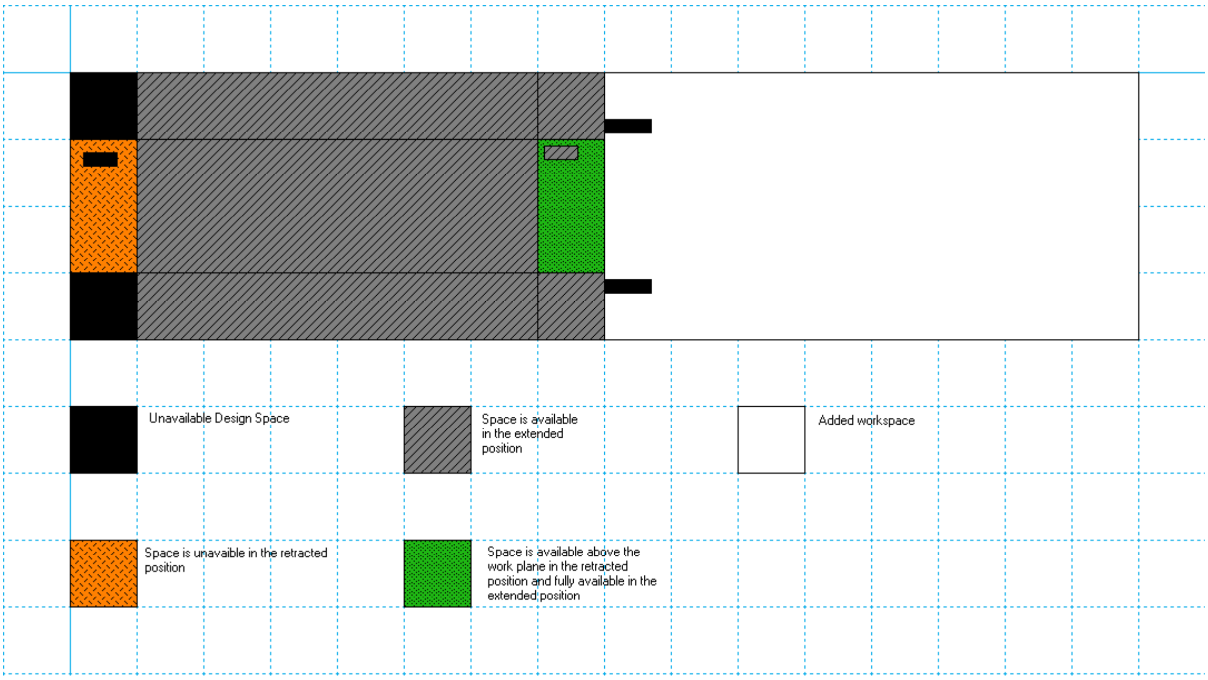

Fig. 9 Self-Closing Mechanism Structural Requirements

One of the changes made to the design process was the use of conceptual software in the development of structural requirements.

Figure 9 above shows the structural requirements used in the case study. Defining the structural requirements directly in the conceptual software allows for defining the workspace and then developing and iterating through the concepts all using the software, thus speeding up the process.

Several other small modifications were made to the design process during this stage. No major modifications were made. The design process described in section 5 above is the final version.

7 Conclusions and Recommendations

An effective methodology, concentrating on conceptual design, was developed for the design of locking mechanisms within linear slides. This process however is incomplete and there is room for improvement.

7.1 Modifications to the Process

The process only focuses on the design of a single locking mechanism within the linear slide. A process, which incorporates the design of all the locking mechanisms at once, could be more effective. However, the process developed in this project is effective, in that it is a reliable process to design locking mechanisms. Additional testing should be conducted to insure that the process works for all types of locking mechanisms.

7.2 Future Work

Emphasis was not placed on the use of computers or artificial intelligence for concept generation, however research has been conduct in this field. With the development of artificial intelligence it is possible for the computer to generate ideas rather than the engineer. This is done through genetic and continuum-based algorithms, which were beyond the scope of this project. Genetic algorithms could increase the speed and reliability at which CIS is able to generate new concepts.

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[27] Wikipedia Inc, 2007, "Image:Mint box polypropylene lid.JPG - Wikipedia, the free encyclopedia," http://upload.wikimedia.org/wikipedia/commons/c/c7/Mint_box_polypropylene_lid.JPG.

Appendix A: Components

Member Types

See Fig. 1 (p. 10) for an illustration of the member types.

1. Cabinet member: the member that is attached to the router/server rack and does not move.
2. Intermediary member: the member that is between the cabinet member and the chassis member.
3. Chassis member: the member that the server is attached to, which is attached to the intermediary member.

Locking Mechanisms

Locking mechanism is the mechanism that can connect two members together and prevent their relative motion and the mechanism which controls the connecting mechanism. Some locking mechanisms can also move the members prior to locking them. Disconnect mechanisms and self-closing mechanisms are sub-types of locking mechanisms. Locking mechanisms' components are the lock and release mechanism.

Lock

Lock is the mechanism that can prevent the relative motion of the members it connects, and possibly move the members prior to preventing their relative motion.

1. Front lock can prevent the relative motion of the chassis and the intermediary members.
2. Rear lock can prevent the relative motion of the intermediary and the cabinet members.
3. Staging lock is designed to allow for the translation of the intermediary and chassis members until the intermediary reaches its maximum extension, at which point it is locked into place by this lock and the chassis continues to travel freely.
4. Disconnect mechanism's lock is the system of elements that prevents the complete extension of the chassis out of the intermediary.

5. Self-closing mechanism's lock is the system of elements that moves the intermediary and the chassis into the fully retracted position.

A lock can be in one of two states:

1. Locked lock: the mechanism that is in the state of preventing the relative motion of the members it connects.
2. Released lock: the mechanism that is in the state of letting the members it connects translate.

A lock consists of several key elements (it does not have to have every single one of these elements):

1. Obstacle: the feature or a trap / hole that is attached to or is part of a different member from the one locking element is attached to. The obstacle is normally stationary. Figure 10 below shows the housing of a front locking element. The obstacle's purpose is to interact with the locking element when the members are to be moved / locked.

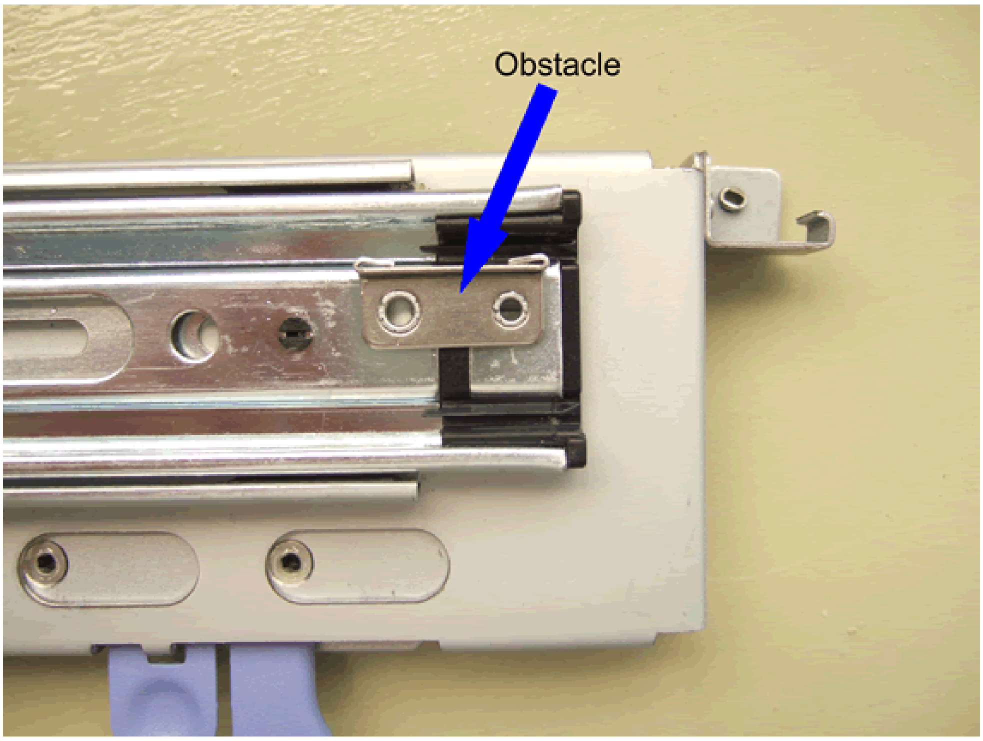


Fig. 10 Obstacle
(from CIS 611-10190 slide)

2. Locking element: the component that interacts with the obstacle; when the locking element is engaged with the obstacle and the obstacle is preventing its motion, the lock is the locked state; when it is not engaged, the lock is in released state. See Fig. 11 below for an illustration of the locking element.

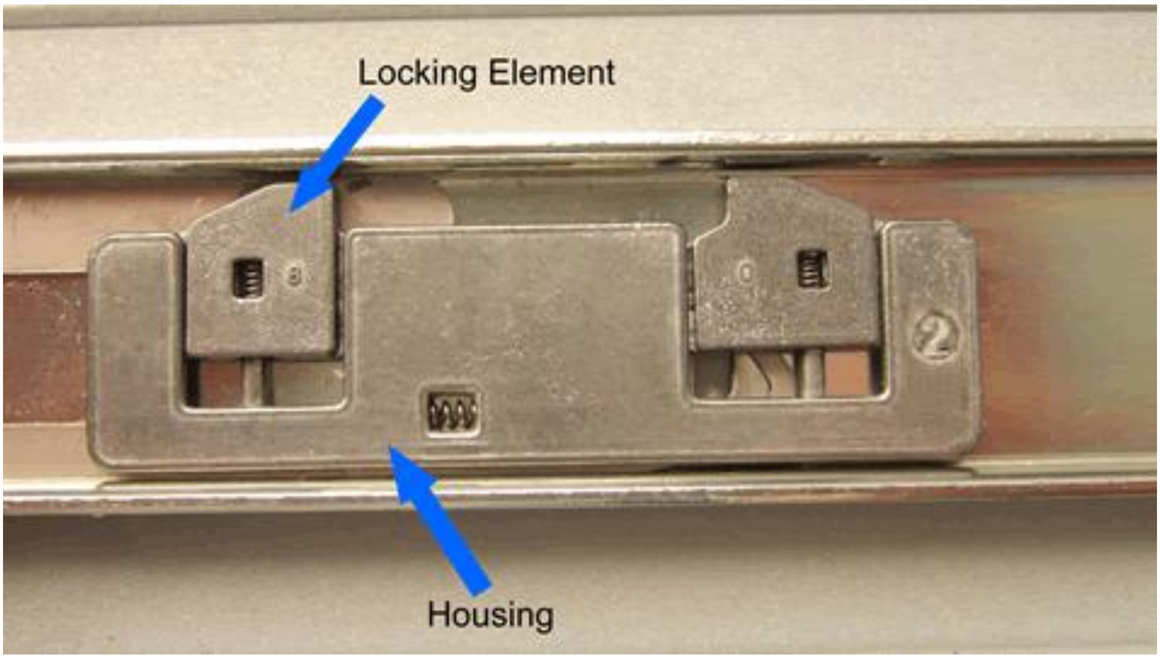


Fig. 11 Lock Components
(from CIS 611-10190 slide)

3. Housing: the component that restricts the motion of the locking element. See Fig. 11 above for an illustration of the housing. Not every lock has a housing.

Release Mechanism

Release mechanism is a mechanism that lets the user change the state of the lock from locked to released. A release mechanism consists of several key elements (it does not have to have every single one of those elements):

1. Switch: the component(s) that the user directly interacts with. See Fig. 12 below for an illustration of the switch mechanism. The release mechanism only has a switch if it is to be activated by the user. Rear and staging locking mechanisms and self-closing mechanisms have no switch. Some versions of the switch can be:

a. Button

b. Lever

c. Slider

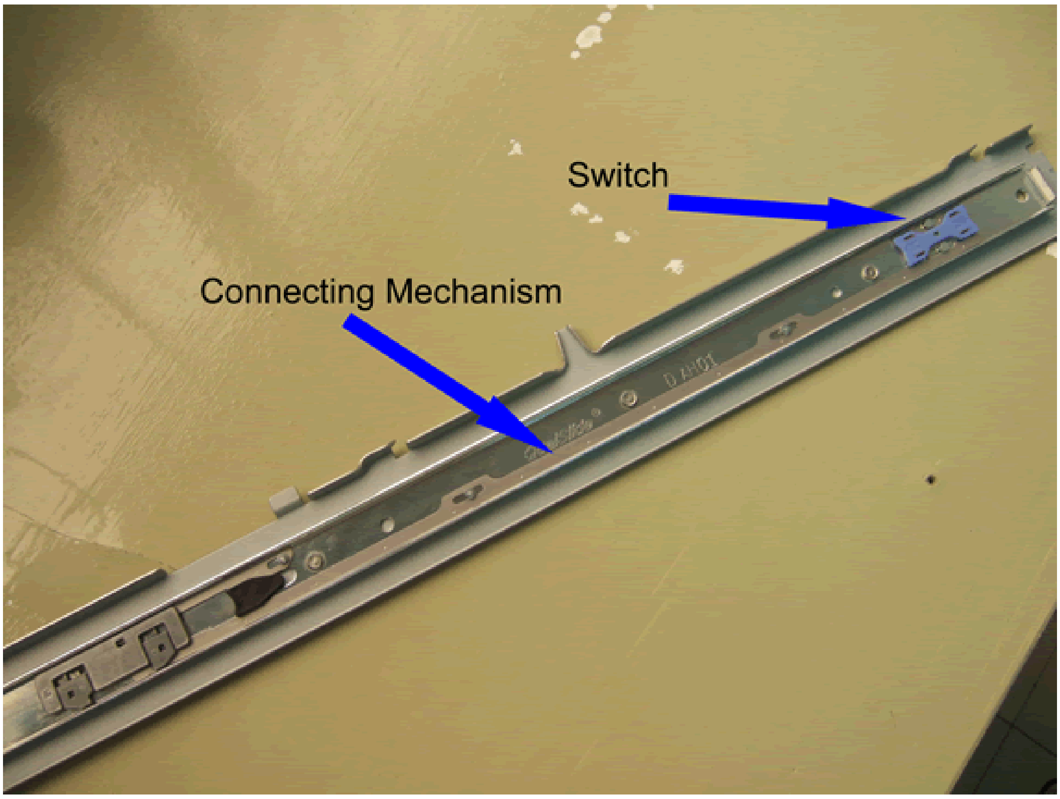


Fig. 12 Release Mechanism Components
(from CIS 611-10190 slide)

2. Connecting mechanism: the component(s) that connects the lock mechanism and the switch mechanism or the driver of the release mechanism. See Fig. 12 above for an illustration of a connecting mechanism. Some connecting mechanisms can be:

    a. Connecting rod/bar (in a prismatic joint with ground)

    b. A pin-jointed linkage

Disconnect Mechanism

Disconnect mechanism is a mechanism that prevents the chassis from completely extending out of the chassis and the intermediary member. It is a sub-type of a locking mechanism.

Self-closing Mechanism

Self-closing mechanism is a mechanism that allows the chassis and the intermediary members to automatically fully retract into the cabinet when they are within a set distance (usually 2”) from the fully retracted position. It is a sub-type of a locking mechanism.

Appendix B: CIS's History

Table 5 CIS's History Milestones

1955	CIS is founded in Grand Prairie, TX to supply small mechanical components and tooling for North America market.
1967	CIS expands capabilities in North America to include Sheet Metal Stamping and Fabrication Division.
1990	CIS expands capabilities in North America to include Die Cut Manufacturing Division.
1996	Asia-Pacific CIS Pte. LTD (APCIS) established in Singapore to provide logistics services for the Pacific Rim market including planning, materials management, assembly and sales.
1998	CIS Grand Prairie, TX achieves ISO registration.
1999	CIS Houston, TX and APCIS Singapore achieve ISO registration.
1999	CIS Europe LTD subsidiary established in Glasgow, Scotland to provide logistics services for the European market including planning, materials management, assembly and sales.
2000	APCIS expansion in Wuxi, China includes metal stamping, fabrication, assembly, and logistics.
2001	CIS Houston, TX achieves transition to ISO 9001:2000 from ISO 9002:94. This improved level of ISO registration includes Engineering certification in addition to Manufacturing certification.
2002	APCIS Singapore achieves transition to ISO 9001:2000 from ISO 9002:94. This improved level of ISO registration includes Engineering certification in addition to Manufacturing certification.
2002	APCIS Wuxi, China achieves ISO 9001:2000 registration.
2003	CIS Grand Prairie achieves transition to ISO 9001:2000 from ISO 9002:94. This improved level of ISO registration includes Engineering and Manufacturing certification.

Appendix C: Personal Communication with Al Barry, CEO of CIS

Below is the text of the e-mail received from Al Barry, describing CIS's design process and problem they were facing:

```
      From:  Al Barry
To: "CIS Slide Lock Project Team, Sponsors and Advisors"
      Conversation: RE: Current Project Summary
Subject: RE: Current Project Summary
Greetings all,
The primary objective of the project is to develop a standard design
process for a slide feature such as the rear slide lock.  This process
could then be used or modified for use to design a front lock, or a
sequencing lock, or a remote lock releasing mechanism, or other mechanical
devices.
At present all new locking features are designed from concepts from one or
more engineer's experiences.  So a lock may be a latch, or a lever, or a
cam because an engineer previously solved a problem with a latch, or a
lever, or a cam.  But the ideal design process should consider the function
of the feature, the loads to be experienced, the space available for the
mechanism, etc.  Then a list of possible devices may be considered, or a
combination of these devices, to achieve the desired performance
objective.  The ideal process should utilize kinematics theory and linkage
synthesis to develop new mechanism concepts.  Our present design process is
based on experience and not all known theory or all known mechanisms.
It is my belief that many specific software packages or kinematics
algorithms are now available for use by our designers.  These tools could
be used to synthesize a linkage that could perform a locking action, or
release a previously set lock.  I think one or more of these software tools
```

can be included in specific steps of the design process to support the final 3D model. This model is then subject further analysis such as FEA and load testing of prototypes.

Our present design flow may look like this:

Simple feature requirement (e.g., lock slides when open, manual release to close)

Concept (from engineer experience and sketches)

Design calculation (free body diagram and analysis of loads and forces)

Design solid model (Pro-E 3D model)

Finite element analysis of critical areas (Pro-Mechanica)

Prototypes and testing

Manufacturing feasibility and cost

Final design

A new or ideal design process flow may look like this:

Definition of feature requirements (detailed feature specifications)

Conceptual design possibilities (idea generation)

Design idea prioritization (idea reduction)

Design idea selection

Design calculation (free body diagram and analysis of loads and forces)

Design solid model (Pro-E 3D model)

Finite element analysis of critical areas (Pro-Mechanica)

Prototypes and testing

Manufacturing feasibility and cost

Final design

The obvious difference between the 2 design process examples is at the front end of the process. That is where I would like to apply more science and exhaust more known mechanisms and combinations of mechanisms to develop new, unique, and hybrid mechanisms. Then I would like to synthesize the mechanisms and model the mechanisms to compare against the desired functions.

Please advise if you have other questions.

Al

Al Barry, CEO

APCIS Wuxi

Appendix D: Design Process E-mail Survey Form

This survey was sent out over e-mail to three CIS design engineers.

• What is your name?

• What is your position here at CIS?

• How long have you been working at CIS?

• Have you been involved in any part of the slide lock / release mechanism design?

❖ If yes:

○ What customer requirements are you given?

○ Has it ever happened that you did not have any customer requirements?

❖ If so, what did you follow as your design requirements?

○ Do you create a list of design requirements?

○ Do you create slide locks individually or as part of a team?

❖ If on a team:

▪ What aspect of the project are you responsible for?

▪ Does the entire team start the design together, or do people get added in or out at certain stages of the design process?

▪ How does the teamwork in general take place? Do people come up with alternative designs and then pick the best, or does the entire team work on one design? Or is it something else?

○ Are you ever involved with the conceptual design stage of the design process? The conceptual design stage is the part where the engineers pick the general shape of the lock, such as: a spring that pushes a locking element in the slot, or a flat spring, or a cam with two followers, and so on.

❖ If you are ever involved with the conceptual design stage of the design process…

▪ Do you generate a few ideas before modeling in Pro/ENGINEER?

❖ If so, how do you choose the best idea?

▪ Do you ever modify previous designs to work as the new design?

❖ If so, how do you select an old design to be modified?

▪ Do you sketch concepts for designs on paper, or in some sketching ("conceptual design") software?

▪ What else do you do before building the first Pro/E model? Specifically – is there any particular process that you follow?

❖ If so, do you know if all CIS design engineers follow this process when designing a slide lock / release system?

▪ Could you please recall the first conceptual design of a slide lock that you have ever done? Could you talk about the process?

❖ If so, is it the same as your current design process, or are there differences? What are they?

▪ Whatever your current process is – are you satisfied with it, or would you like to see specific changes done to it? What are they?

Appendix E: Design Process E-mail Survey Response

This is the response received from one of CIS's design engineers; it was chosen as the most insightful one.

• What is your name? *Goh Chong Beng.*

• What is your position here at CIS? *Principal Engineer.*

• How long have you been working at CIS? *4 years.*

• Have you been involved in any part of the slide lock / release mechanism design? *Yes.*

❖ If yes:

○ What customer requirements are you given?

Furniture slide - Other drawers to be locked in closed state if one of it is opened

Appliance slide -

○ Has it ever happened that you did not have any customer requirements? *No*

❖ If so, what did you follow as your design requirements? *Space constraint, simplicity, unique.*

○ Do you create a list of design requirements? *No.*

○ Do you create slide locks individually or as part of a team? *Both*

❖ If on a team:

▪ What aspect of the project are you responsible for? *Slide profile design, slide configuration design, mechanism design.*

▪ Does the entire team start the design together, or do people get added in or out at certain stages of the design process? *Some of each.*

▪ How does the teamwork in general take place? Do people come up with alternative designs and then pick the best, or does the entire team work on one design? Or is it something else? *Most of the time, yes, we try to come out with at least 2 designs.*

○ Are you ever involved with the conceptual design stage of the design process? The conceptual design stage is the part where the engineers pick the general shape of the lock, such as: a spring that pushes a locking element in the slot, or a flat spring, or a cap with two followers, and so on. *Yes.*

❖ If you are ever involved with the conceptual design stage of the design process…

▪ Do you generate a few ideas before modeling in Pro/ENGINEER? *Yes, by sketches.*

❖ If so, how do you choose the best idea? *Simplicity, perceived reliability and robustness, manufacturability, cost, etc.*

▪ Do you ever modify previous designs to work as the new design? *No.*

❖ If so, how do you select an old design to be modified?

▪ Do you sketch concepts for designs on paper, or in some sketching ("conceptual design") software? *Yes, sketches.*

▪ What else do you do before building the first Pro/E model? Specifically – is there any particular process that you follow? *Check other existing design patents to avoid design infringement.*

❖ If so, do you know if all CIS design engineers follow this process when designing a slide lock / release system? *No.*

▪ Could you please recall the first conceptual design of a slide lock that you have ever done? Could you talk about the process? *Interlock design.*

Process: understand required mechanism function - review competitor's sample – design conceptualization (sketches) – design review with design manager – Pro/E mechanism design – design review - prototype mechanism concept for trial – design improvement.

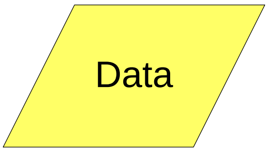
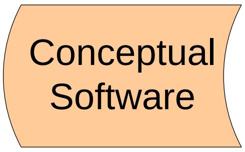
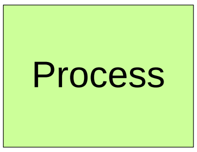
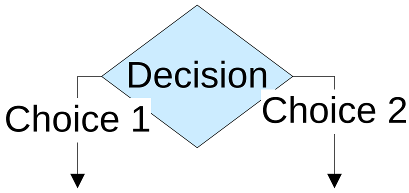
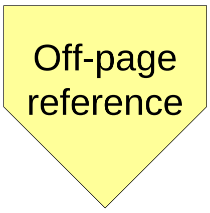
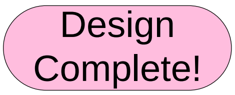
❖ If so, is it the same as your current design process, or are there differences? What are they? *Slightly different, I do patent review for every new design request.*

▪ Whatever your current process is – are you satisfied with it, or would you like to see specific changes done to it? What are they? *I am fine with it but it is time consuming. A more engineering approach is ever better.*

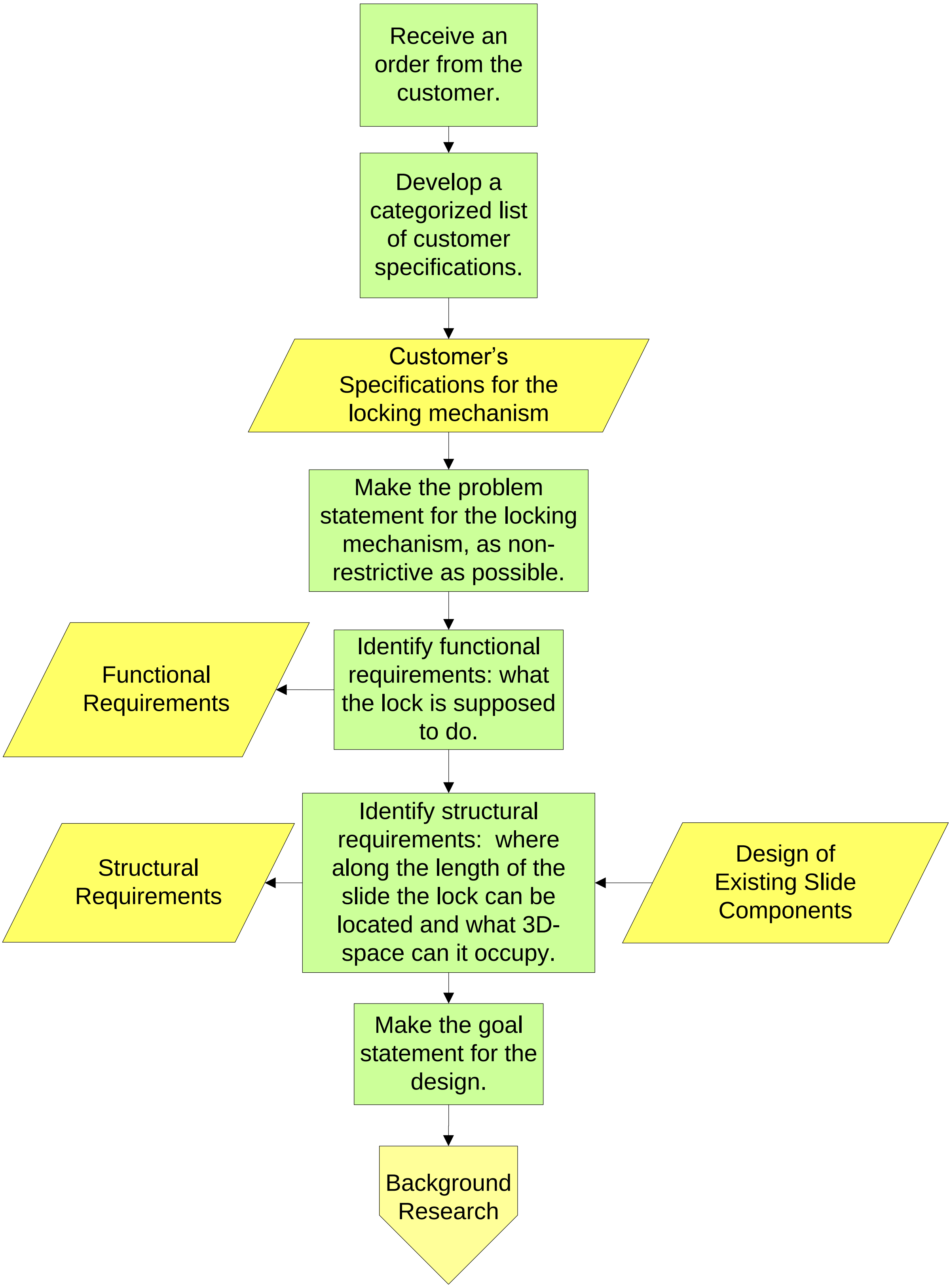
Appendix F: Design Process Flowchart

Design Process Flowchart Legend

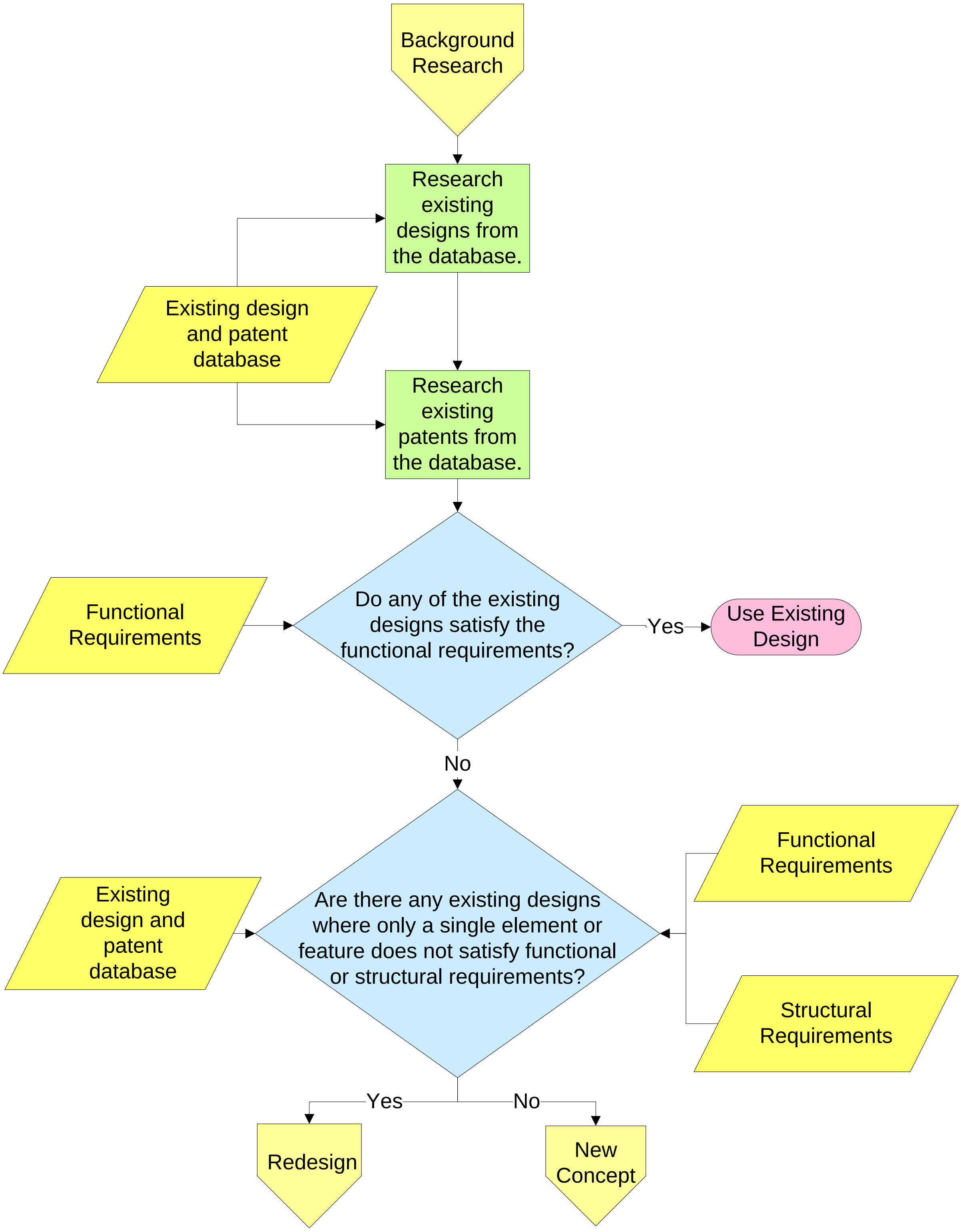
Table 6 Design Process Flowchart Legend

Symbol	Meaning
	The Data symbol contains some data – a piece of information that will be useful at certain steps of the design process. The steps that use the particular piece of data are linked to it with an arrow, pointing at the step. The steps that generate a particular piece of data are linked to it with an arrow, pointing at the data.
	The Conceptual Software symbol contains the software that may be useful at the step in the process that this symbol is linked to.
	The Process symbol contains a process – some action to be completed by the engineer.
	The Decision symbol contains a decision – a point in the design process where the design process splits into two different paths.
	The Off-page Reference symbol links two pages together. If it is at the bottom of the page it links to a following page, and if it is at the top of the page it links to a preceding page.
	The Design Complete symbol indicates the end of the process.

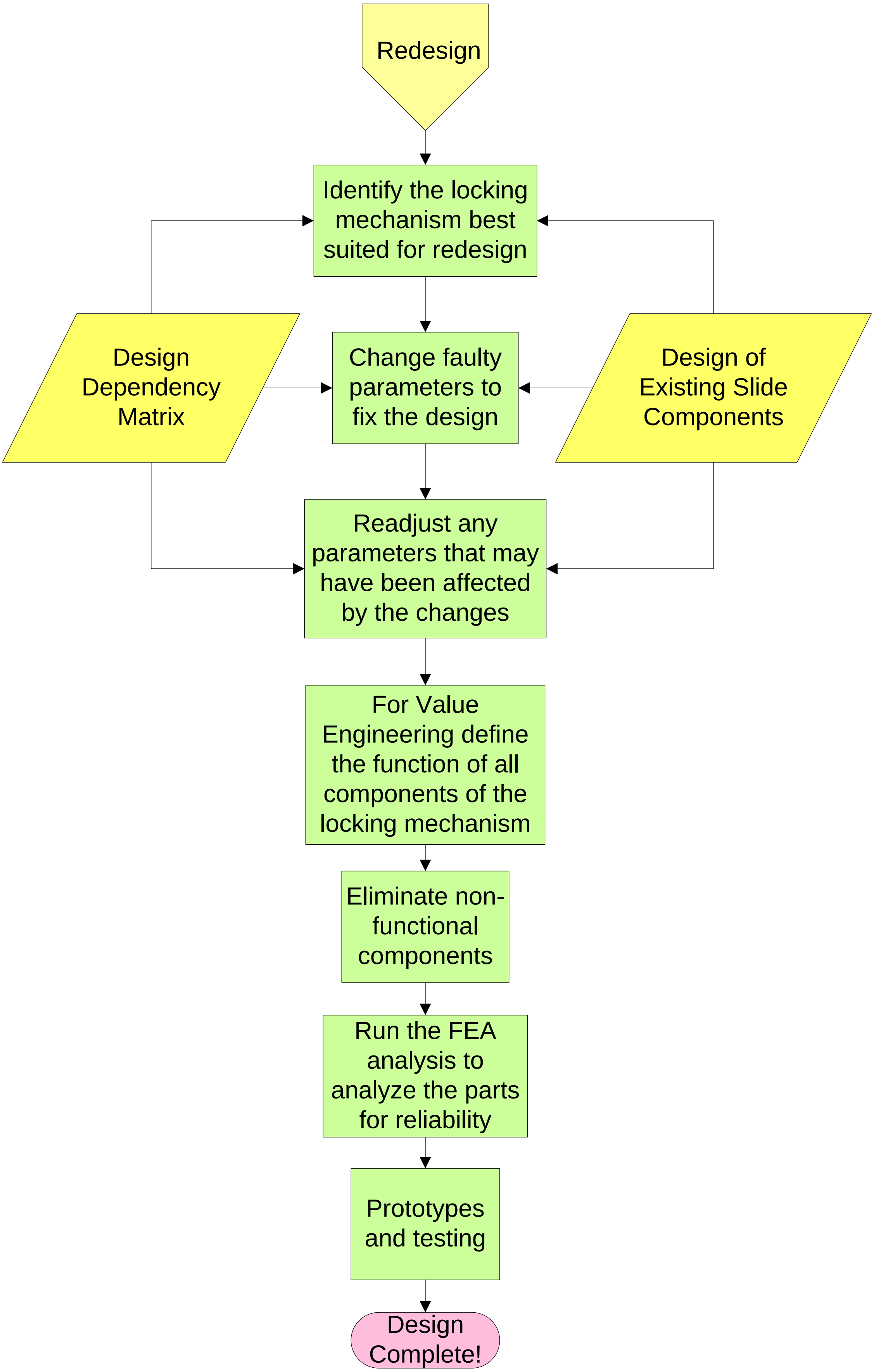
Problem Definition



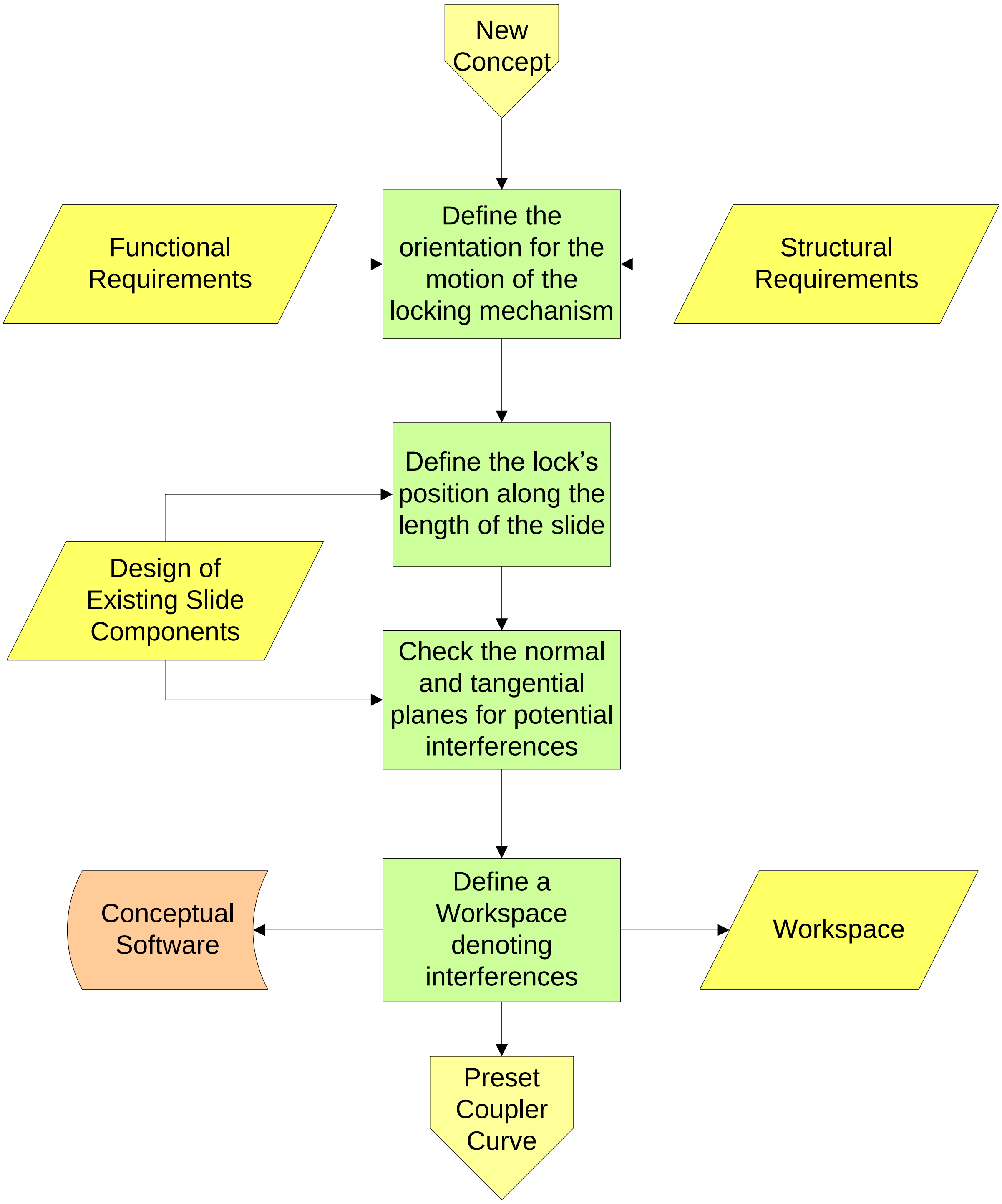
Background Research



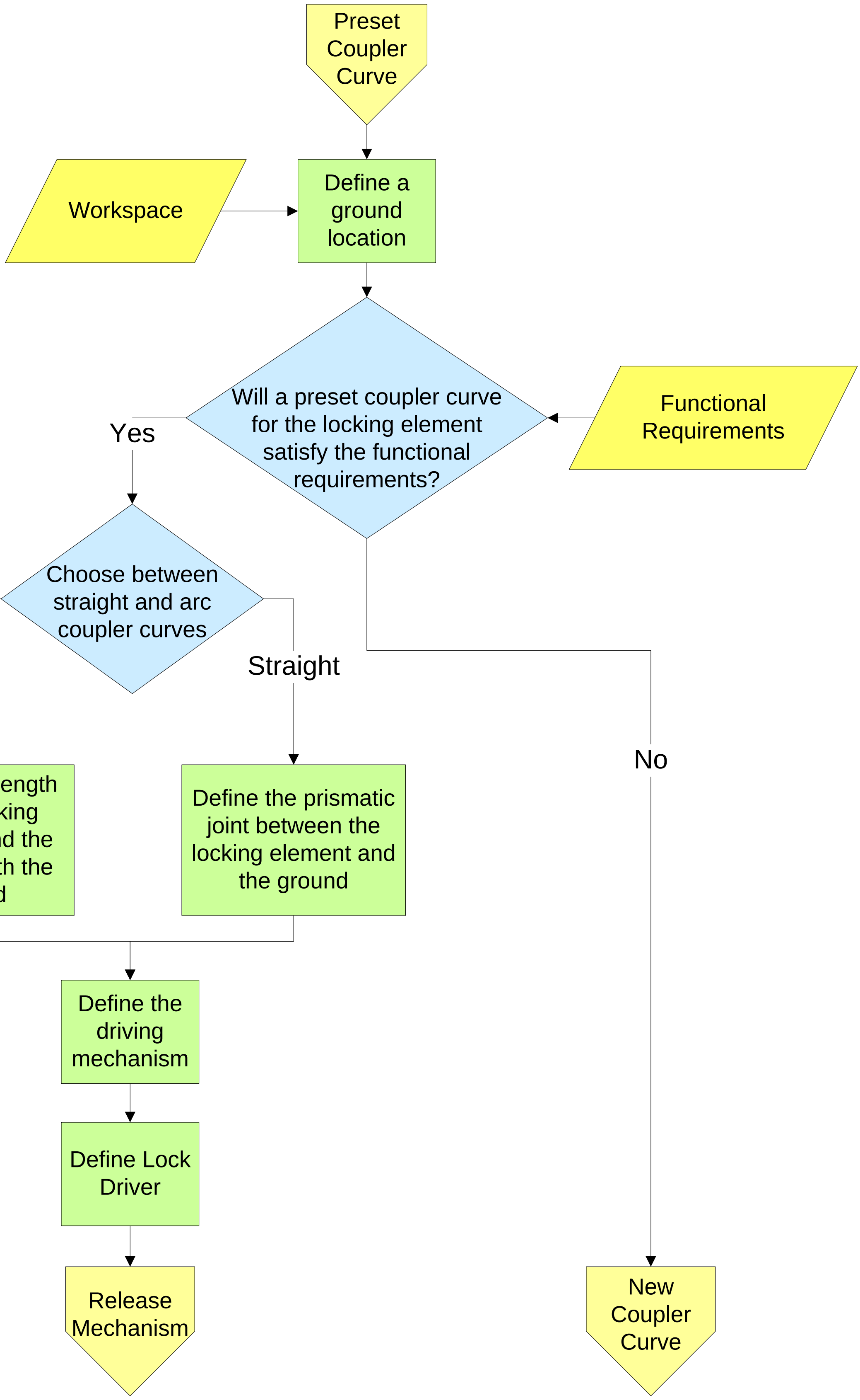
Redesign


Redesign
Identify the locking mechanism best suited for redesign
Design Dependency Matrix
Change faulty parameters to fix the design
Design of Existing Slide Components
Readjust any parameters that may have been affected by the changes
For Value Engineering define the function of all components of the locking mechanism
Eliminate non-functional components
Run the FEA analysis to analyze the parts for reliability
Prototypes and testing
Design Complete!

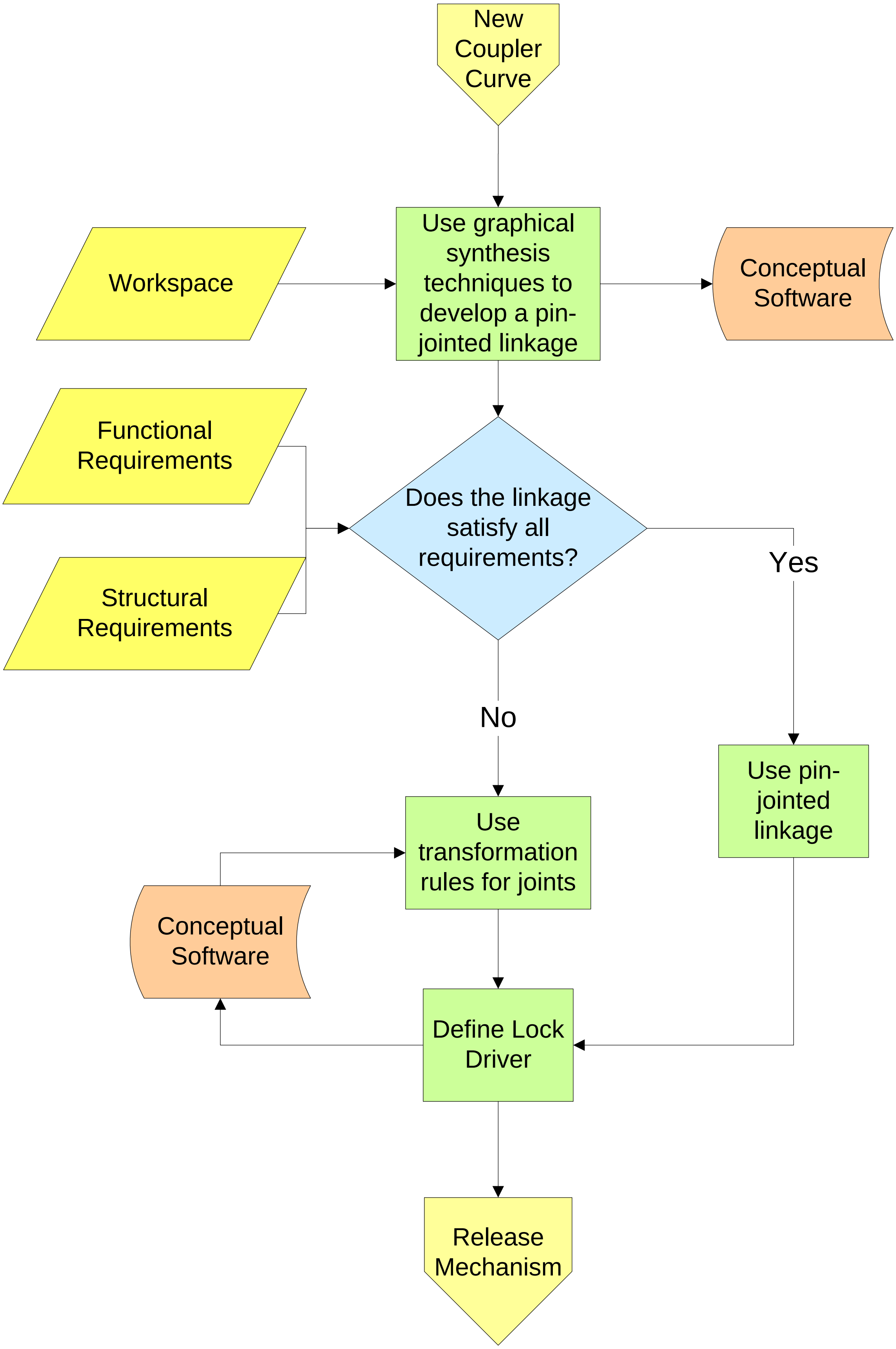
Workspace Definition



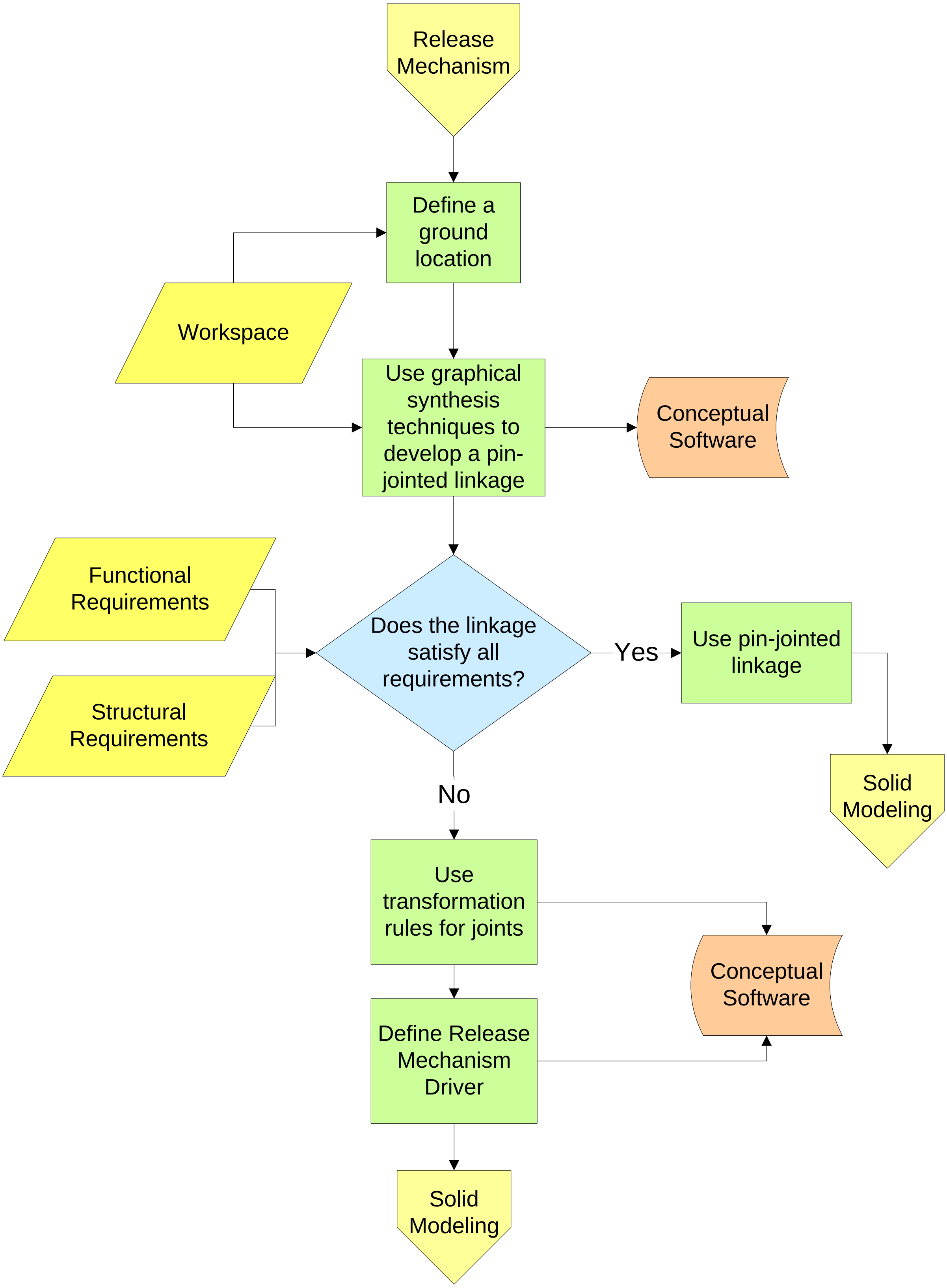
Preset Coupler Curve



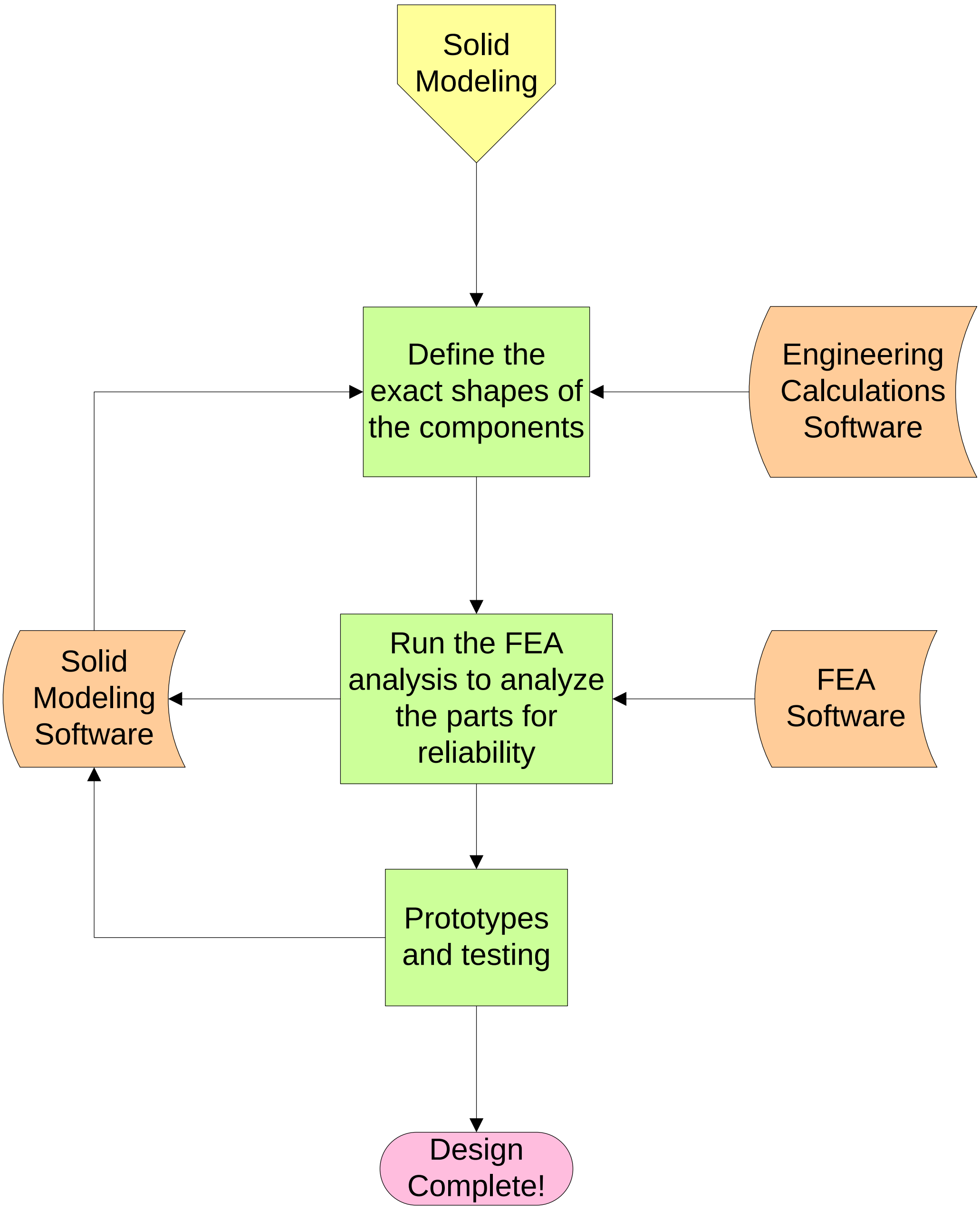
New Coupler Curve



Release Mechanism



Solid Modeling



Appendix G: Database

Locking Mechanism	Type	Design Parameters				
		Lock				
		Length (in)	Height (in)	Width (in)	Type of Locking Element	Number of Features on Locking Element
Existing Mechanisms						
Locking Mechanism 1	Front lock	1.14	0.79	0.08	Straight spring slider	5
Locking Mechanism 2	Front lock	1.02	0.79	0.08	Flat spring slider	4
Locking Mechanism 3	Other	2.48	0.43	0.16	Flat spring	4
Locking Mechanism 4	Front lock	2.95	0.43	0.39	Flat spring trap	6
Locking Mechanism 5	Rear lock and staging lock	0.51	0.51	0.31	Torsion spring slider	6
Locking Mechanism 6	Rear lock	1.85	0.79	0.31	Rotating element	7
Locking Mechanism 7	Rear lock	1.42	0.79	0.39	Pin-slider element	7
Patents						
Yang's 6979067	Front lock				Flat spring	6
Yang's 7029080	Front lock				Latch slider	6
20050017614	Front lock				Flat spring trap	9
20020089272	Front lock				Torsion spring rotating element	3
6764149	Front lock				Flat spring	4
6296338	Front lock				Flat spring	3
6926377	Front lock				Flat spring	4
3995927	Front lock				Rotation hook	3
6929339	Front lock				Torsion spring slider	8

Database continued.

Locking Mechanism	Design Parameters			
	Lock			
	Type of Obstacle	Number of Features on Obstacle	Type of Housing	Number of Features on Housing
Existing Mechanisms				
Locking Mechanism 1	Barrier	3	Track	3
Locking Mechanism 2	Barrier	3	Track	4
Locking Mechanism 3	Trap	1	Hole	1
Locking Mechanism 4	Pin	2		
Locking Mechanism 5	Barrier	2	Track	2
Locking Mechanism 6	Barrier	3	Axis	1
Locking Mechanism 7	Barrier	3	Axis	1
Patents				
Yang's 6979067	Trap	5		
Yang's 7029080	Barrier	5	Track	2
20050017614	Pin	1		
20020089272	Barrier	13	Axis	1
6764149	Trap	1		
6296338	Trap	1		
6926377	Trap	3		
3995927	Trap	1	Axis	1
6929339	Pin	1	Axis	1

Database continued.

Locking Mechanism	Release Mechanism						
	Length (in)	Height (in)	Width (in)	Type of Connecting Mechanism	Number of Features on Connecting Mechanism	Type of Switch	Number of Features on Switch
Existing Mechanisms							
Locking Mechanism 1	14.76	0.83	0.08	Rod	4	Slider	4
Locking Mechanism 2	14.76	0.83	0.08	Rod	4	Slider	4
Locking Mechanism 3							
Locking Mechanism 4							
Locking Mechanism 5							
Locking Mechanism 6							
Locking Mechanism 7							
Patents							
Yang's 6979067							
Yang's 7029080				Rod	10	Slider	4
20050017614							
20020089272				Torsion spring	2	Tab	
6764149							
6296338							
6926377							
3995927							
6929339				Rod	1	Button	1

Database continued.

Locking Mechanism	Performance Parameters							
	Lock	Release Mechanism	Lock	Release Mechanism	Lock	Release Mechanism	Ease of release	Presence of Pinch Point
	Manufacturability		Assemblability		Dependence on Compliant Elements			
Existing Mechanisms								
Locking Mechanism 1	2	1	3	2	3	4	4	No
Locking Mechanism 2	2	1	3	2	3	4	4	No
Locking Mechanism 3	5	5	5	5	4		5	No
Locking Mechanism 4	5	5	5	5	4		5	Yes
Locking Mechanism 5	3		4		2			No
Locking Mechanism 6	5		4		2			No
Locking Mechanism 7	4		4		3			No
Patents								
Yang's 6979067	5	5	5	5	4		5	Yes
Yang's 7029080	3	1	3	2	5	4	4	No
20050017614	3	5	5	5	4		5	Yes
20020089272	1		3		3			No
6764149	5	5	5	5	4	4	5	Yes
6296338	5	5	5	5	4	4	5	Yes
6926377	5	5	5	5	4	4	5	Yes
3995927	5	5	5	5	3	3	4	Yes
6929339	2	3	3	3	2	3	4	No

Appendix H: Design Dependency Matrix

Block 1.

Table 7 Block 1 of Banded DDM

	Lock Length	Lock Height	Lock Width	Type of Locking Element	Number of Features on the Locking Element	Type of Obstacle	Number of Features on the Obstacle	Type of Housing	Number of Features on the Housing
Lock Manufacturability									
Lock Assemblability									
Lock Geometric Constraints									
Lock Dependence on Compliant Elements									
Lock Scalability									
Impact Resistivity									
Push/Pull Resistivity									

Block 2.

Table 8 Block 2 of Banded DDM

	Release Mechanism Length	Release Mechanism Height	Release Mechanism Width	Type of Connecting Mechanism	Number of Features on the Connecting Mechanism	Type of Switch	Number of Features on the Switch
Release Mechanism Manufacturability							
Release Mechanism Assemblability							
Release Mechanism Geometric Constraints							
Release Mechanism Dependence on Compliant Elements							
Release Mechanism Scalability							
Ease of release							
Presence of Pinch Point							

Appendix I: Database and DDM Terminology

The names of the components and mechanisms are all given in Appendix A: Components above, and are used below. This appendix describes all of the other terminology used in the database (see Appendix G: Database above) and in the design dependency matrix (see Appendix H: Design Dependency Matrix above).

Database and DDM are subdivided into design and performance parameters, all of which are described below.

Design Parameters

Design parameters fully describe the conceptual shape of the locking mechanism, and roughly the size as well. The process of redesign involves just modifying one or more of these parameters; if new design parameters have to be introduced, that is a completely new design.

Design parameters are separated into lock and release mechanism design parameters.

Lock Design Parameters

1. Length, width, height: this category describes how much space the lock occupies. Notice, that this is not the same thing as Lock Scalability, which is approximately how small/large one can make the lock (using the same type of design).
    a. Length: how much space along the horizontal direction from the back of the slide to the front the lock occupies; roughly, measured in inches.
    b. Width: how much space along the horizontal direction normal to the right or left wall of the server the lock occupies; roughly, measured in inches.
    c. Height: how much space along the vertical direction, in the plane of the server the lock occupies; roughly, measured in inches.
2. Type of Locking Element: see Appendix A: Components above.

3. Number of Features on Locking Element: this category describes the number of features on the locking element. A feature is a round, extrusion, chamfer, etc.
4. Type of Obstacle: see Appendix A: Components above.
5. Number of Features on Obstacle: this category describes the number of features on the obstacle. A feature is a round, extrusion, chamfer, etc.
6. Type of Housing: see Appendix A: Components above.
7. Number of Features on Housing: this category describes the number of features on the housing. A feature is a round, extrusion, chamfer, etc.

Release Mechanism Design Parameters

1. Length, width, height: this category describes how much space the release mechanism occupies. Notice, that this is not the same thing as Release Mechanism Scalability, which is approximately how small/large one can make the release mechanism (using the same type of design).
    a. Length: how much space along the horizontal direction from the back of the slide to the front the release occupies; roughly, measured in inches.
    b. Width: how much space along the horizontal direction normal to the right or left wall of the server the release mechanism occupies; roughly, measured in inches.
    c. Height: how much space along the vertical direction, in the plane of the server the release mechanism occupies; roughly, measured in inches.
2. Type of Connecting Mechanism: see Appendix A: Components above.
3. Number of Features on Connecting Mechanism: this category describes the number of features on the connecting mechanism. A feature is a round, extrusion, chamfer, etc.
4. Type of Switch: see Appendix A: Components above.
5. Number of Features on Switch: this category describes the number of features on the switch. A feature is a round, extrusion, chamfer, etc.

Performance Parameters

Performance parameters describe, essentially, how good the lock is. Potential customer requirements should be (in some form) in these parameters, along with general qualities that may not be important to the customer but are important for the manufacturer.

1. Lock Manufacturability: this category describes how manufacturable the individual parts of the lock are. See Table 9 below for details on this parameter. Notice, that number of features should also be considered for determining manufacturability.

Table 9 Lock Manufacturability Rubric

Value	Description
5	Can be manufactured in only one step by stamping.
4	Requires more than one step to stamp. Does not require bending. Or, can be easily die cast or molded.
3	Requires more than one step to stamp, including bending. Or can be die cast or molded with some difficulty.
2	Requires machining.

2. Release Mechanism Manufacturability: this category describes how manufacturable the individual parts of the release mechanism are. See Table 10 below for details on this parameter. Notice, that number of features should also be considered for determining manufacturability.

Table 10 Release Mechanism Manufacturability Rubric

Value	Description
5	The release mechanism is part of the lock , and can be manufactured with only one step by stamping.
4	Requires more than one step to stamp. Does not require bending. Or, can be easily die cast or molded.
3	Requires more than one step to stamp, including bending. Or can be die cast or molded with some difficulty.
2	Requires machining.

3. Lock Assemblability: this category describes how easy it is to assemble the lock and how prone its assembly is to errors. See Table 11 below for details on this parameter.

Table 11 Lock Assemblability Rubric

Value	Description
5	Having one component that is riveted to the slide.
4	Having two components that are riveted to the slide.
3	Having three components, some of which are tiny, and are assembled by riveting.
2	Having more than three components, some of which is tiny, and they are assembled by riveting.
1	Having more than three components and some components are tiny, and are assembled by ways other than riveting.

4. Release Mechanism Assemblability: this category describes how easy it is to assemble the release mechanism and how prone its assembly is to mistakes. See Table 12 below for details on this parameter.

Table 12 Release Mechanism Assemblability Rubric

Value	Description
5	The release mechanism is part of the lock.
4	Just one component, which is riveted to the slide.
3	Have two components, some of which is tiny, and they are assembled by riveting.
2	Have three components, some of which is tiny, and they are assembled by riveting.
1	Have more than three components, and some components are tiny, to assemble them needs other ways except riveting.

5. Lock Dependence on Compliant Elements: this category describes how dependent the lock is on compliant elements, which are an out-of-house, less than ideally reliable part and thus if possible should be avoided. See Table 13 below for details on this parameter.

Table 13 Lock Dependence on Compliant Elements Rubric

Value	Description
5	Having no compliant element.
4	Containing only one compliant element. If the spring fails, the lock still works without getting stuck.
3	Containing only one complaint element. If the spring fails, the lock will get stuck, and cannot work well.
2	Containing only one complaint element. If the spring fails, the lock does not work at all.
1	Containing more than one complaint element.

6. Release Mechanism Dependence on Compliant Elements: this category describes how dependent the release mechanism is on compliant elements, which are an out-of-house, less than ideally reliable part and thus if possible should be avoided. See __ for details on this parameter.

Table 14 Release Mechanism Dependence on Compliant Elements Rubric

Value	Description
5	Having no compliant element.
4	Containing only one compliant element. If the spring fails, the release mechanism still works without getting stuck.
3	Containing only one compliant element. If the spring fails, the release mechanism will get stuck, and cannot work well.
2	Containing only one compliant element. If the spring fails, the release mechanism does not work at all.
1	Containing more than one compliant element.

7. Ease of Release: this category describes how easy it is to release the lock on this locking mechanism. See Table 15 below for details on this parameter.

Table 15 Ease of Release Rubric

Value	Description
5	A gentle touch releases the locking mechanism (less than 0.5 lbf).
4	A push releases the locking mechanism (between 0.5 lbf and 2 lbf).
3	A strong push releases the locking mechanism (greater than 2 lbf).

8. Lock Scalability: this category describes approximately how small/large one can make the lock (using the same type of design). This performance parameter is only included in the DDM, for redesign purposes.
9. Release Mechanism Scalability: this category describes approximately how small/large one can make the release mechanism (using the same type of design). This performance parameter is only included in the DDM, for redesign purposes.
10. Presence of Pinch Point: this category describes whether or not the user can pinch himself / herself when releasing the lock.