Redesign of the SureTrack Grader Transfer Bin Using Axiomatic Design Theory

Kristján Gerhard

Thesis of 30 ECTS credits
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Thesis of 30 ECTS credits submitted to the School of Science and Engineering
at Reykjavík University in partial fulfillment of
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Abstract

The SureTrack grader manufactured by Marel is equipped with transfer bins for grading of whole salmon. Two issues are related with the transfer bins themselves, the bins are expensive to manufacture and cracks in the weld joining the sides of the bin have been observed. The objective of the project is to redesign the SureTrack bin to achieve more strength at a lower cost, the redesigned bin shall be fully compatible with the drive system of the SureTrack grader as well as lending itself to application as a transfer system.

Axiomatic Design theory was employed during the redesign of the bin. The Customers Needs were defined from the attributes seen as desirable by the client, the Customer Needs were used to define Functional Requirements and Design Parameters for the bin at multiple levels. A new bin was designed according to the chosen Design Parameters.

Analysis of the design was twofold. Firstly the strength of the bin and its welds was estimated using finite element analysis A study was designed where the skewing loads suspected to be the cause of the cracking of the welds were simulated. Software was used to estimate the manufacturing cost of the bin once all costing parameters had been defined. For comparison purposes analyses were performed on both bins.

The findings are that the cost of manufacturing the redesigned bin is around 12% less than the cost of manufacturing the SureTrack bin while at the same time being about 47% stronger for the load case analysed.

Endurhönnun flutningskörfu SureTrack flokkarans eftir Axiomatic Design fræðum

Kristján Gerhard

janúar 2016

Útdráttur

SureTrack flokkari Marel er búinn flutningskörfum til flokkunar á heilum laxi. Tvö vandamál hafa verið viðloðandi hönnun körfunnar, í fyrsta lagi þykir karfan dýr í framleiðslu og í öðru lagi hafa komið fram vandamál þar sem að suður í körfunni hafa sprungið. Verkefnið miðar að því að endurhanna SureTrack körfuna á þann hátt að ná megi fram meiri styrk fyrir lægra verði, hin endurhannaða karfa skal passa í SureTrack flokkarann og jafnframt vera nothæf í flutningskerfi án flokkunar. Við endurhönnun á körfunni var farið eftir Axiomatic Design hönnunarfræðum, þar sem þarfir viðskiptavinarins voru skilgreindar útfrá þeim kostum sem sóst var eftir í endurhannaðri körfu. Þarfir viðskiptavinarins voru notaðar til að útfæra hagnýtar kröfur til búnaðarins sem síðan myndaði grunn að hönnunarforsendum og var ný karfa hönnuð eftir þeim forsendum.
Greining á körfunni var tvíþætt. Í fyrsta lagi með tilliti til styrks og í öðru lagi með tilliti til kostnaðar. Framkvæmd var finite element greining á körfunni til að meta spennur í henni og suðum hennar. Mat höfundar var það að sprungur í suðum körfunnar mæti rekja til breytilegs álags sem gerði það að verkum að karfan væri að skekkjast. Greining var því hönnuð sem líkti eftir slíku álagi. Sértækur hugbúnaður var notaður til að meta framleiðslukostnað eftir að forsendur höfðu verið skilgreindar. Til samanburðar voru báðar greiningarnar framkvæmdar á sama hátt fyrir báðar körfurnar.
Niðurstöður verkefnisins eru þær að endurhönnuðu körfuna er unnt að framleiða með um 12% minni tilkostnaði en karfan er jafnframt um 47% sterkari miðað við það álagstilfelli sem skoðað var.

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Master of Science

In memory of my mother. She would have been proud.

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List of Abbreviations

POM	Polyoxymethylene
CN	Customer Needs
FR	Functional Requirements
DP	Design Parameters
PV	Process Variables
DM	Design Matrix
TIG	Tungsten Inert Gas
CNC	Computer Numerical Control
AISI	American Iron and Steel Institute
EN	European Norm
ASTM	American Society for Testing and Materials
FEA	Finite Element Analysis
RD	Redesigned
ST	SureTrack
ISK	Icelandic Króna
USD	US Dollar

Chapter 1

Introduction

The SureTrack grader is successfully used in salmon processing by Marel's customers to sort and batch fish for sale. Although the SureTrack grader has been successfully used its use has not been without problems. The SureTrack transfer bins have developed fatigue fractures along a weldline in the main structural assembly of the bin.

Speculation has been within Marel's industry centre that caters to the fish industry of using the SureTrack concept as a base for a transportation system to supplement Marel's current inventory of transportation solutions. A second possible application of a redesigned SureTrack bin is as a part of an infeed station.

1.1 Scope

The objective of this project is to evaluate whether the design of the bin can be improved upon by employing systematic design tools. The redesigned bin should be usable as a drop in replacement in the SureTrack grader, fitting the original bin's footprint, as well as lending itself to the possible use in a transportation system based upon the primary design aspects of the SureTrack grader.

In order for the bin to be usable in a transportation system or in an infeed station it is necessary that the bin's discharge mechanism be operable independent of the bins travelling direction.

The objectives of the project are

- Evaluate an appropriate design framework.
- Design a replacement bin for the SureTrack grader using the selected framework.
- Evaluate the feasibility of the design.

1.2 Thesis Structure

This thesis is divided into six chapters.

- The first chapter is an introduction to the project and contains a brief description of the problem which is to be solved, project objectives and primary conclusions.
- The second chapter is a collection of necessary background information, this includes an overview of Marel, the SureTrack grader, and the SureTrack bin.

- The third chapter reviews the Axiomatic Design theory.
- The fourth chapter details the application of the AD framework for the design of the solution and the outcome of the design is reviewed.
- The fifth chapter details the analyses performed on the redesigned bin and the SureTrack bin, and their results.
- The sixth chapter contains a discussion on the results of the project, as well as the possibilities of further work related to the project.

1.3 Primary Conclusions

The SureTrack bin was redesigned using the Axiomatic Design framework, for comparison identical analyses were performed on both the SureTrack bin and the redesigned bin. The primary conclusions of the project are twofold.

Firstly the redesigned bin, designed using the Axiomatic Design framework is mechanically stronger than the current version of the SureTrack bin, with observed stresses approximately 47 % lower than those in the SureTrack bin, and should therefore be better able to resist the skewing believed to be a primary factor in the premature failure of the bin.

Secondly the redesigned bin promises to be cheaper to manufacture than the SureTrack bin, by margin of approximately 12 % according to a costing analysis. A compilation of manufacturing metrics indicates that while the redesigned bin requires more cutting and forming of sheet metal, there is less welding involved and fewer parts require manufacturing in a machine shop. This shift from relatively expensive manufacturing techniques to cheaper ones, as well as the fact that the redesigned bin does without some expensive purchased items, result in the savings observed.

Chapter 2

Background

This chapter contains background material relevant to the project. The chapter is divided into sections starting with a brief overview of Marel and the Marel manufacturing environment, proceeding to an overview of the SureTrack grader and the transfer bins.

2.1 Marel

Marel hf. is one of Iceland's leading high technology companies, one of the countries largest manufacturing companies and a large software company rolled into one. Marel employs around 500 people at their office and production facility in Garðabær Iceland, and over 4000 people worldwide, where it operates offices and subsidiaries in over 30 countries [1]. The company specialises in advanced integrated systems for the fish, meat, poultry, and further processing industry where it sells a wide range of equipment including scales, graders, portioners, x-ray machines, dynamic weighing systems and de boning machines. These products are sold as individual units and as a part of large scale flow lines. Marel is highly dedicated to innovation and annually invests 5-8 % of its income in research and development[2].

2.1.1 Manufacturing at Marel

Marel's manufacturing operation is divided into 4 individual divisions known as workshops.

Sheet steel workshop A large part of Marel's products are created from laser cut and bent sheet steel ranging in thickness from 1 to 12 mm. The sheet steel workshop is equipped with carbon dioxide (CO_2) lasers and press brakes.

Welding workshop Marel employs both manual and automatic welding techniques. Welders use TIG welding to assemble and create structural elements and sub assemblies Industrial robots fitted with welding equipment are used to weld high volume parts such as displays, electronic junction boxes and scale platforms.

Turning and milling workshop The turning and milling centre handles custom fabricated steel and plastic parts. The workshop has extensive manufacturing capabilities including CNC lathes and CNC mills. A separate of section of the workshop fabricates items from plastic sheet material.

Assembly workshop The assembly workshop takes parts from the other workshops and workers assemble the parts into working machinery and equipment.

2.1.1.1 Surface Treatment

All steel items manufactured at Marel are surface treated to achieve certain properties. Nearly all welded assemblies are bead blasted with glass media before further assembly. This process gives the steel a pleasing matte appearance which is a unique feature of Marel's products. Despite the aesthetically pleasing nature of the glass blasted surfaces, the glass blasting process leaves the surface, rough making the treatment impractical for use on surfaces where the food products shall slide. Therefore these surfaces are either acid washed or sent to a subcontractor for electroplating which yields a much smoother surface.

2.2 SureTrack Grader

One of Marel's products is a whole salmon grader. The grader's primary function is to selectively create batches of fish of the same quality level and as close to a predefined weight as possible. The grader is equipped with two parallel conveyors fitted with bins in the central area between the conveyors. The bins act as buffers for fish pushed off the conveyors by computer controlled arms. Once the predefined batch is created it is dropped onto a conveyor within the frame of the grader which transports it to a boxing station. Another version of the salmon grader is called the SureTrack grader and its design is quite dissimilar to the design of the grader previously described. The SureTrack grader utilizes open bins which are loaded from the top and emptied by levering a mechanism which opens the bottom of the bins. The bins are driven by a pair of drive chains on an elliptical path.

The cycle of the bins through the grader shown in Figure 2.1 is as follows. A single salmon is mechanically dropped into each bin at the infeed to the grader (1). The bin traverses the end of the grader while loaded and makes its way to the upper half of the grader (2). Here the bin approaches the discharge section of the grader, where its content is dropped into the buffers (3). It's also possible for the loaded bin to traverse the second end of the grader to the lower level where the bins can be emptied into tubs or boxes (4). The batches in the buffers are dropped into the empty bins on the lower level when ready and transported to a boxing station just in front of the infeed(5), the boxed salmon is ejected from the grader and the cycle repeats.

The SureTrack grader has a rated throughput of 120 fish per minute (fpm) but is also available in a 60 fpm version where every other transfer bin is omitted. The output options of the SureTrack grader are $25\,\mathrm{kg}$ batches in styrofoam boxes and $1000\,\mathrm{kg}$ batches in plastic tubs [3]. The SureTrack concept has some unique and interesting features. The use of discharging transport bins compared to designs incorporating regular conveyor belts is the openness of the grader itself and the area immediately surrounding the transfer bins. This openness provides for easy access to all parts of the SureTrack grader for easy cleaning, a critical part of food processing. Another unique feature of the SureTrack grader is the fact that it's operation takes place on two different levels and transfer of the product from one level to the other is an integral part of the grader.

2.2.1 SureTrack Bins

The bins of the SureTrack grader (Figure 2.2) serve the purpose of transporting the fish between the infeed and out feed of the grader. The bins are designed to be able to transport single fish or a batch of fish weighing up to $25\,\mathrm{kg}$ [3]. The bin is made entirely out of 1.4301 stainless steel, an identical material to AISI 304, except for bushings in the discharge mechanism and the support wheels, and the support wheels themselves.

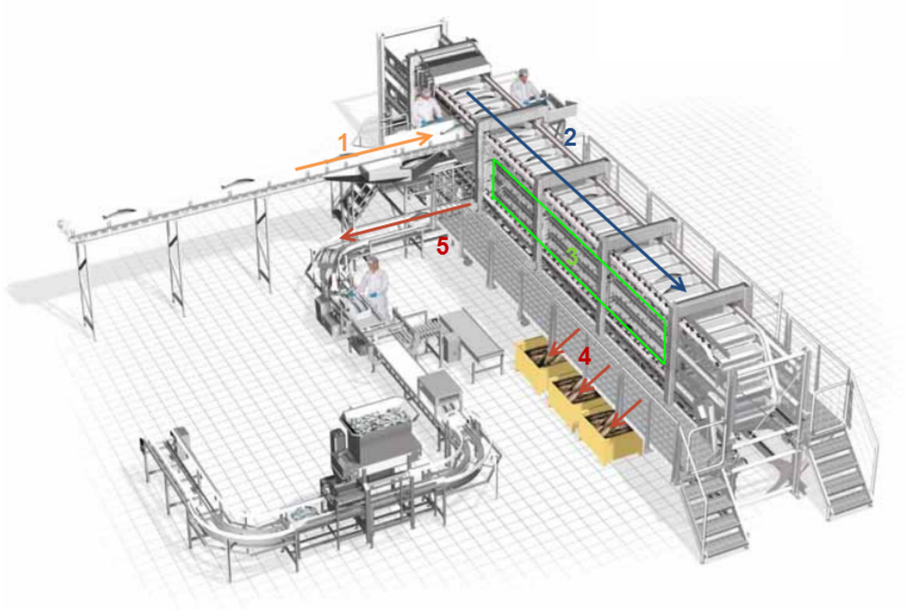

Figure 2.1: The SureTrack grader. Whole salmon is fed into the grader at the infeed (1). The salmon is mechanically dropped into the transfer bins which transfer the salmon to the upper section (2). The salmon is discharged into buffers (3) or tubs (4). The buffered salmon is discharged from the buffers when the batches are ready into empty transfer bins and moved to the boxing section where the salmon is discharged from the grader (5)[3]

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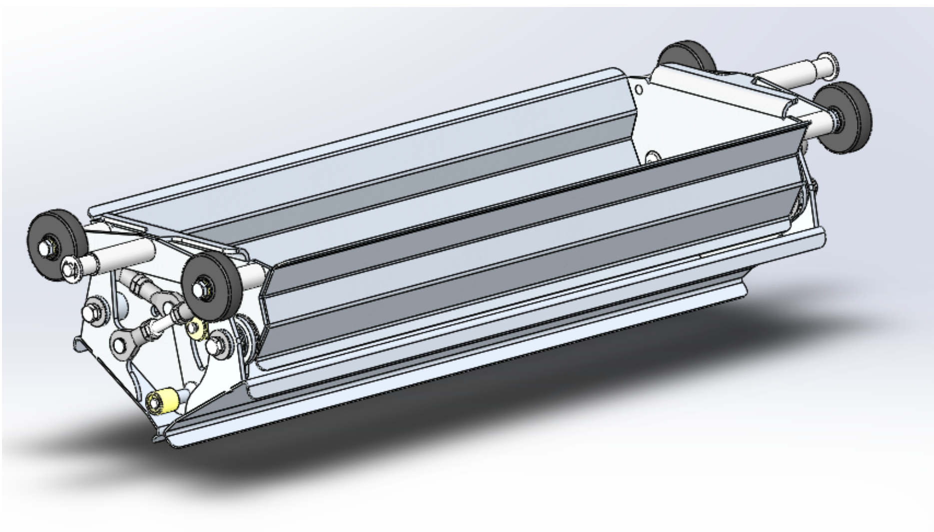


Figure 2.2: The SureTrack bin

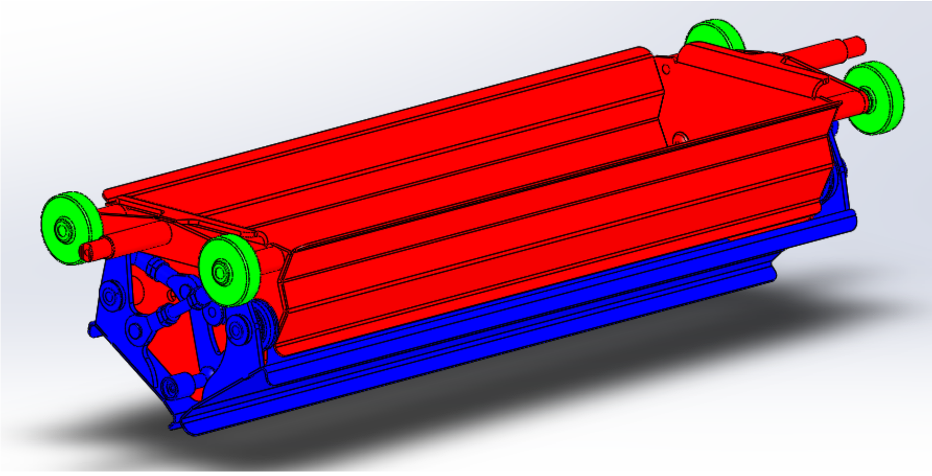


Figure 2.3: The SureTrack bin elements. Main weldment is coloured red, support system is coloured green and the discharge system is coloured blue.

2.2.1.1 Elements of the SureTrack Bin

The SureTrack bin can functionally be split into three separate elements. The primary element onto which the other two are attached is the main weldment, the discharge system and the support system form the rest of the SureTrack transfer bin.

These elements of the SureTrack bin are shown in Figure 2.3, the main weldment is coloured red, the discharge system is coloured blue and the support system is coloured green. Each element is made up of a number of custom built parts and sub-assemblies, the total part count for the SureTrack transfer bin and each element respectively is presented in Table 2.1.

Table 2.1: SureTrack bin part count.

Element	Sheetsteel	Turned&milled	Purchased†	Totalpartcount
Main weldment	6	12	0	18
Support system	0	4	8	12
Discharge system	10	22	20	52
Total	16	38	28	82

† Purchased items does not include standard bolts and washers.

Main Weldment

The main weldment, shown in Figure 2.4, of the SureTrack bin is comprised of four pieces of laser cut and bent sheet steel and six turned weldnuts which form an attachment point for the discharging system. Originally the entire weldment was constructed of $2.5\,\mathrm{mm}$ sheet steel. However cracking in the welded corner intersections between the long sides and gable ends forced a review of the design. Marel's mechanical designers believed that the cracking was due to fatigue resulting from the constant loading of fish by dropping it into the bin. This prompted a design change in the gable ends increasing the thickness of the sheet steel to $5\,\mathrm{mm}$. The long sides are bent into an "s" shape in order to increase the stiffness and resistance to bending, both in the horizontal and vertical direction. A bent tab on the gable ends is welded onto the vertical support bar of the carrier system to increase the stiffness of the carrier system.

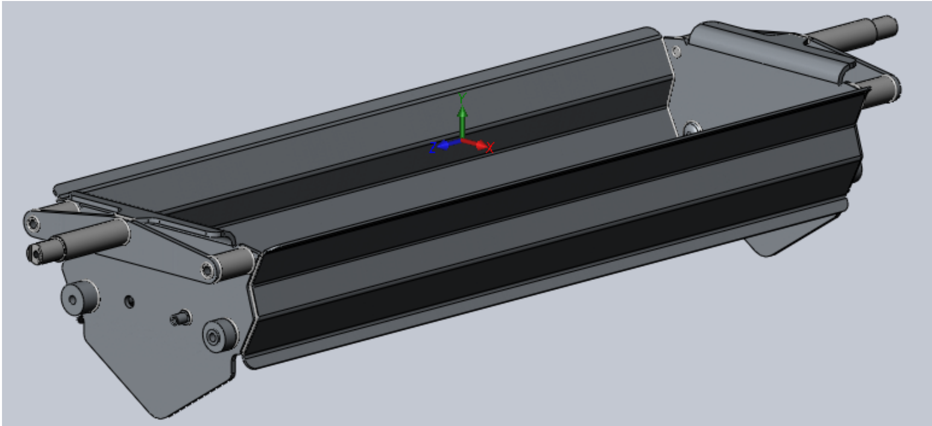


Figure 2.4: The SureTrack bin main weldment.

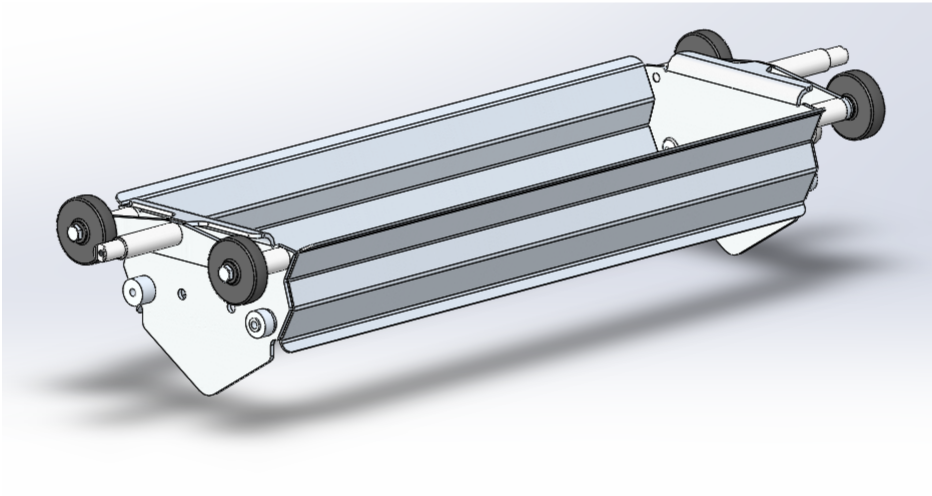


Figure 2.5: The SureTrack bin carrier system and main weldment.

Support System

The support system, shown in Figure 2.5, bears the weight of the bin and drives it on its path around the grader. while on its linear path between the ends of the elliptic path of the grader the bins are supported by the wheels, while traversing the semicircular path at the ends of the grader, the bin is supported by its chain mount. The mounting pylons of the carrier system are welded to the vertical support bar for the support pin and the main weldment of the bin. The wheels are made of POM (Polyoxymethylene) chosen for its low friction and excellent machinability and bolted onto the support pylons. The wheels turn in IGUS iglide bushings commonly used by Marel. The wheels ride on rails mounted to the grader frame.

There are two reasons for supporting the bin in this manner instead of suspending it from the drive chain. Firstly the wheels prevent the bin from spinning when the force from the cam used to operate the discharge system in applied. Secondly suspending a number of these bins would make an unsupported drive chain sag affecting the vertical location of the bin, this would make the vertical positioning of the cams used to engage the discharging mechanism variable with the horizontal position of the bin within the grader frame. An option to counter this would be to support the chain and somehow operate it in a track or on a rail. The friction caused by the combined weight of the chain, bins and fish would cause excessive wear on the chain and cause jerky motion in the chain drive.

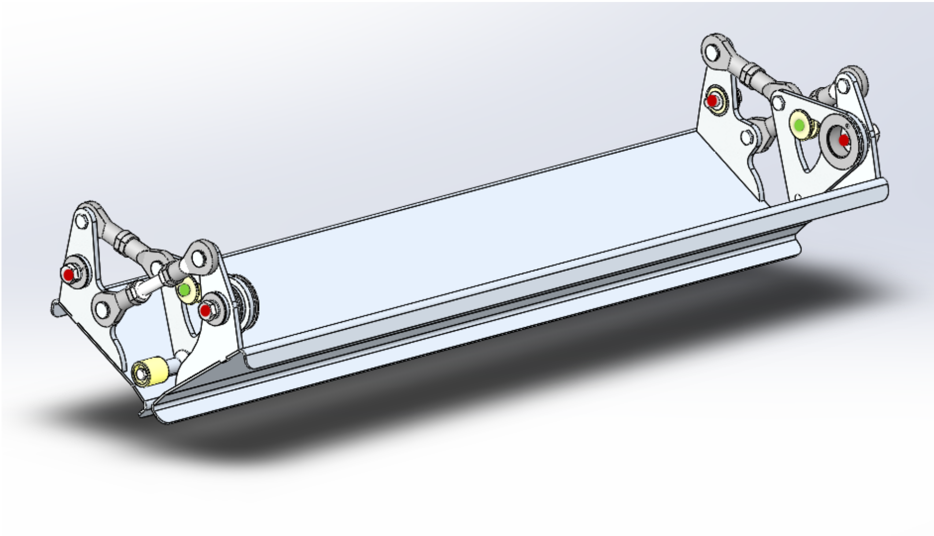
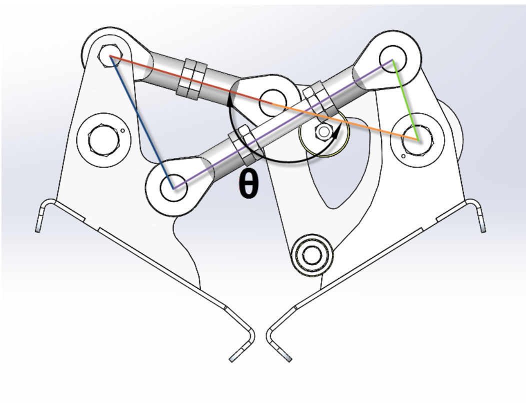
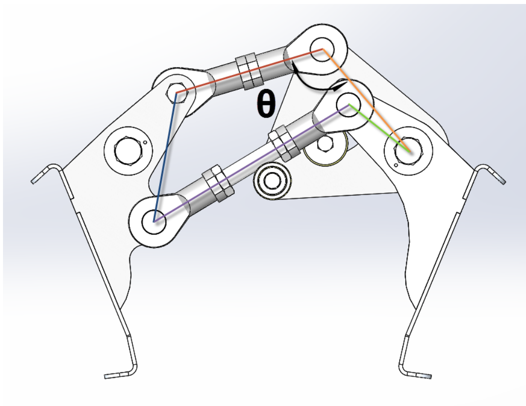


Figure 2.6: The SureTrack bin discharge system. The red points indicate the pivot points for the discharge system, attached to weldnuts on the main weldment. The green points indicate the guides used to prevent shift of the activation arm of the system and to provide a stop once the bin is locked.



(a) SureTrack bin discharge mechanism in the closed position.



(b) SureTrack bin discharge mechanism in the open position.

Figure 2.7: Side view of the SureTrack bin discharge mechanism.

Discharge System

The discharge system, shown in Figure 2.6, is by far the most complex part of the transfer bin, consisting of 52 parts, or about 60% of the total part count of the SureTrack bin.

The discharge system is directly mounted to the main weldment using the six previously mentioned weldnuts, four weldnuts form pivot points for the discharge system and two are attachment points for guides which prevent shifting of the activating arm of the system. The geometry of the discharge system forms a linkage system with 5 links, the geometry is designed so that the weight of the product resting on the doors of the discharge system aids the release of the product once discharge has been triggered.

This feature essentially makes the discharge system unstable in the open position (Figure 2.7b) and in order for the bin to retain product, the discharge must be positively locked in the closed position (Figure 2.7a), this is feature is also accomplished by the geometry of the linkage. The angle θ formed by two of the links is less than $180°$ while the discharge

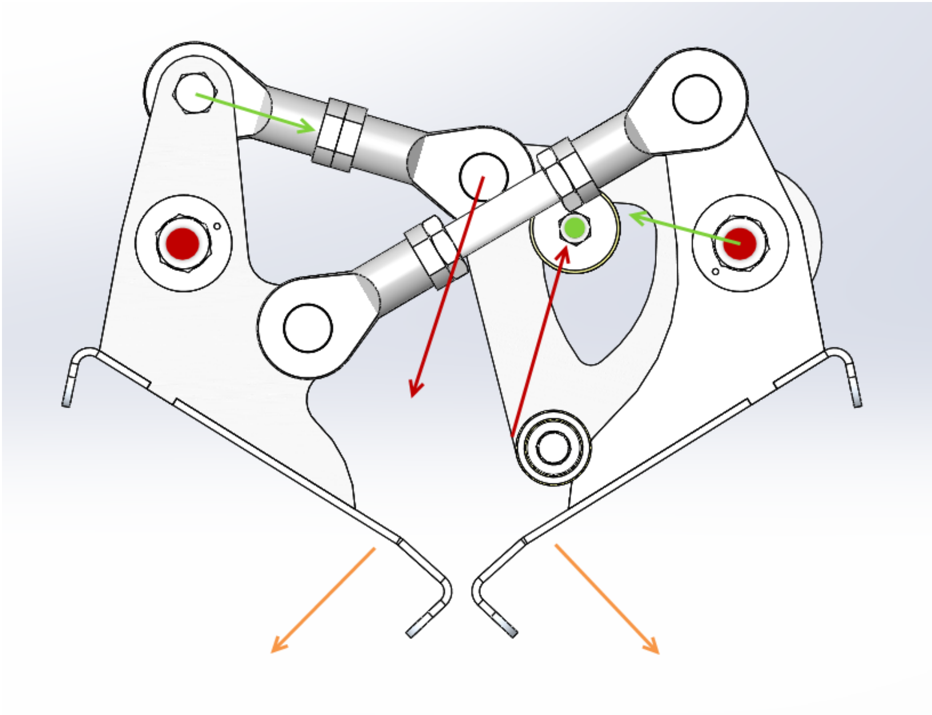
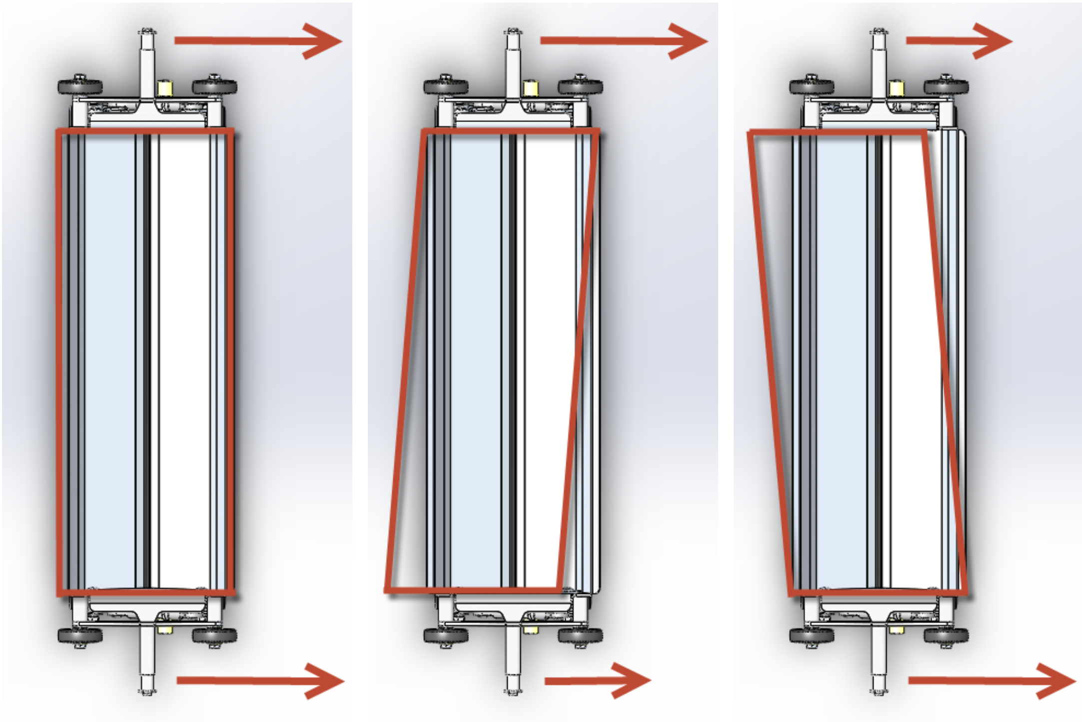


Figure 2.8: Forces within the SureTrack bin discharge system linkage.

mechanism is open, however in the closed position, the angle between the links is greater than $180°$. The effect caused by this is that the bin is self closing when the discharge system is in the closed position. This is easily seen by envisioning a load on the discharge system's doors, this load can be seen in figure 2.8 as orange arrows. The load on the doors generates moment (not pictured) about the doors rotational axis which are marked with red dots in the figure, the forces generated by this moment are transferred to the left door causing the compressive forces, marked with green arrows, between the door and the right doors pivot point. These compressive forces cause the connection point between the links affected to be pushed downward, indicated with red arrows, this movement is hindered by the discharge mechanism movement limiter, indicated with a green dot. This makes the doors of the discharge system impossible to open unless $\theta < 180°$. This design is quite ingenious and follows the principle of self [4], as it is both self-opening and self-closing depending on the alignment of the discharge mechanism activation lever.

Problems With the SureTrack Bin

As noted above, cracking at the weld line between the long sides and the gable ends of the main weldment has been observed. Marel's engineers theorized that the recurring impact from the dropping of the fish into the bin might be causing fatigue cracking in the weld line. The impact might be contributing to the cracking but given the orientation of the joint relative to the loading this does not seem likely. Another cause, which seems plausible, is that uneven forces from the drive system might be inducing parallelogram motion within the main weldment of the SureTrack transfer bin. This possibility is pictured in Figures 2.9a through 2.9c. In Figure 2.9a the forces acting on each side of the bin from the drive chains are equal and the square shape of the main weldment is preserved. In Figure 2.9b the force from the far side drive chain exceeds the force from the near side drive chain causing the parallelogram motion mentioned previously. In Figure 2.9c the inequality of forces is



(a) Equal force acting on the SureTrack bin from both drive chains.
(b) Greater force acting on the SureTrack bin from the near side drive chain.
(c) Greater force acting on the SureTrack bin from the far side drive chain.

Figure 2.9: Unequal forces acting on the SureTrack bin.

reversed, where the near side drive chain is exerting a greater force than the far side drive chain.

This parallelogram motion of the main weldment is presumably only slight, where the difference between the drive points is only a few millimetres or less, however, due to the large span of the SureTrack bin this movement is amplified to fractions of a degree on the welded joint. While this movement is only slight, the motion may become cyclic during the operation of the SureTrack grader, this cyclic movement could be on a frequency much higher than the loading of the bins causing the bins to experience fatigue loading much higher than they were designed to withstand. The cause of this force difference could possibly stem from jerky motion in the drive chain caused by accumulation of debris during the daily operating period of the grader, slight variances in build of the grader or excessive wear. Another possibility is that the alignment of the cams that operate the discharge mechanism of the bins is out by a small amount causing cam to come into contact with the operating lever of the discharge mechanism a fraction of a second before the opposite cam contacts.

As presented in Table 2.1 the total part count of the SureTrack bin are some 86 parts, not counting standard bolts and washers. Of the total part count of the bin, 54 are custom made by Marel and 32 are purchased off the shelf items, the purchased parts consist of bearings and angular bearing rod ends which make up part of the linkage assembly. For a single bin the part count could be disregarded, however considering the fact that a grader has 120 bins making total investment in parts for the bins in a single grader considerable. Should it be possible to simplify the design of the bin, reducing the part count while preserving the function, the effect could be a considerable reduction in the cost of the SureTrack transfer bin.

Table 2.2: SureTrack bin part count in percenteges of each respective category and the total part count.

Element	Sheet steel	Turned & milled	Purchased†	Total part count
Main weldment	37,5%	31,6%	0%	22%
Support system	0%	10,5%	28,6%	14,6%
Discharge system	62,5%	57,9%	71,4%	63,4%
Total	100%	100%	100%	100%

† Purchased items does not include standard bolts and washers.

Converting the values from Table 2.1 into percentages of the respective total part counts for each category and the total part count, and displaying them in a similarly arranged table, it becomes apparent that the discharge system contributes to over 60% of the total part count of the SureTrack bin. It is safe to say that the complexity and part count of the discharge system make it the ideal starting point of the redesign, a reduction in part count of 50% for the discharge system, translates to a 30% reduction in the total part count.

Chapter 3

Methods

The word *design* has different meaning depending on the viewer. For an architect the act of designing is a highly creative process. The architect draws on his experiences and interests, as well as current trends to envision the structure, whether it be building or bridge. The architect sketches something entirely new, something no one has built before. The shapes, colours and materials come together and breathe life into the architects design. For an engineer, design can be the act of determining the size a beam for the architects structure. This process does not involve much creativity and it is safe to say it's almost mechanical in the way the engineer takes certain predefined steps in determining the load on the beam and using known equations to determine the necessary size of the beam. Nevertheless the engineer designed the beam.

Although the two professionals are both designing, one act is very different from the other. The point, however, is not that engineers are drones taking pre-programmed steps and calling it design. The example merely points out the extremes in the meaning of the word design.

Despite being a decidedly systematic process, engineering is at the same time a highly creative process. When the engineer is faced with a task, even a mundane one akin to sizing a beam or selecting a fastener, the engineer has to analyse the problem at hand and use his knowledge, experience and creativity to come up with a solution. The engineers job of problem solving can be very challenging, not only coming with up solutions to the problem at hand but in some cases quantifying the problem itself can prove difficult. There are numerous ways to approach a problem such as the one faced by the design engineer in his quest of problem solving. The method of trial and error is a very basic method of problem solving, it is however unlikely that an optimal solution will be found by employing this method. The method is highly heuristic as the combined knowledge and experiences of the engineer contribute to the solution, implying that the older and experienced the engineer is the better the solution should be, this is not necessarily so.

Engineers and scientists have long since realised this and conducted research into the correlation between problems and their solutions and methodical problem solving. The results from this research culminate in the various design theories and design methodologies. One such system is called Axiomatic Design.

3.1 Axiomatic Design

Axiomatic Design is a design methodology developed by Nam P. Suh and introduced in his book “The principles of design” published by the Oxford University Press in 1990 [5]. Axiomatic Design is a theoretical design framework that employs domains, mappings, axioms and decomposition by zigzagging between the domains, theorems and corollaries [6].

3.1.1 Axioms

A significant part of Axiomatic design are two fundamental axioms that govern the design process. In his book Suh presents the formal statement of the axioms [6]. The first axiom, known as the Independence axiom, reads:

> **"Maintain the independence of the Functional Requirements."**

The Independence axiom is a critical part of the Axiomatic Design framework, as many of its key components are based upon it. The Independence axiom indicates that for a design with two or more Functional Requirements (FRs) the FRs must remain independent of each other. This means that each FR can be satisfied without affecting any of the other FRs. By fulfilling this axiom the designer can make changes to one part of the design without having to redesign another part as a result.

Suh's second axiom, known as the Information axiom, reads:

> **"Minimize the information content of the design."**

The purpose of the Information axiom is to help the designer choose the best design out of a number of possible ones. This is important because any number of designs can satisfy the Independence axiom and prove to be an acceptable solution to the problem at hand since different designers are likely to find different solutions to a given set of FRs. In order to evaluate the effectiveness of a design compared to other seemingly as effective designs the Information axiom is applied. It asserts that "the design with highest probability of success is the best design" [6]. Therefore a design that has the least amount of Functional Requirements and associated Design Parameters (DPs) to satisfy the Customer Needs while simultaneously fulfilling the Independence axiom and maintaining the independence of the Functional Requirements is the best design [7].

3.1.2 Domains

According to Suh's theory the design world consists of four domains; The Customer Domain, the Functional Domain, the Physical Domain and the Process Domain [6]. These domains make up what is apt to call the framework of the Axiomatic Design system as each domain contains a set of requirements or attributes defined by the designer to help guide him through the design process. Figure 3.1 presents a schematic representation of the domain structure. The domains are arranged from left to right where the domain to the left relative to a domain in question indicates what we want to accomplish and the domain to the right relative to the domain in question indicates the proposed solution. The process of going from a what we want to accomplish and how we propose to accomplish it is referred to as mapping.

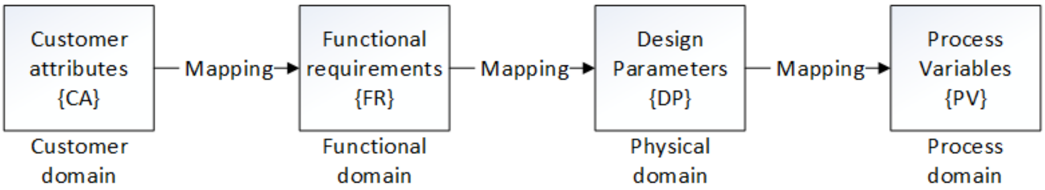


Figure 3.1: Axiomatic Design domains and mappings.

The first domain named by Suh is the Customer Domain, represented by the first block in Figure 3.1. The Customer Domain contains the information relevant to the attributes and benefits that the customer is looking for in a given product, or the "what's" regarding the product, in a set of parameters known as Customer Needs (CNs). The second domain, represented by the second block, is the Functional Domain, in this domain the information from the Customer Domain would be mapped to a set of FRs. These FRs could be considered the "how's" to the Customer Domains "what's". The third domain is the Physical Domain, represented by the third block, where the designer maps the FRs to Design Parameters containing information on how the required functions should be accomplished. This would constitute mapping the "how's" in the Functional Domain describing how we want to accomplish a given parameter to a physical "what", an item, machine or technique. The Process Domain is the last domain named by Suh, and represented by the last block in Figure 3.1. The information contained in the Process Domain, known as Process Variables (PVs) describes again "how" the "what" in the Physical Domain should be manufactured [8].

An example of the four domains described by Suh could be a customer seeking to heat a warehouse to a certain temperature. This information would constitute the CNs in the Customer Domain. The designer then analyses how he could accomplish the customers desires, in the Functional Domain there are several ways to accomplish the task of heating the warehouse such as centralised hydronic system, decentralised electric heat, or centralised forced air systems to name a few. Deciding upon a centralised hydronic system the designer then maps the FRs to a specific way of accomplishing this by choosing an oil fired boiler and forced air convectors. This information constitutes the Design Parameters and as such can be mapped to PVs in the Process Domain. These would for example describe how to manufacture and install such equipment.

3.1.2.1 Domain Levels

The mapping process described in Section 3.1.2 is not a single level process, once the specific attributes the customer seeks have been formalized into a set of CNs and the base level FFs and DPs have been established a series of mapping iterations known as zigzagging [9] begins where the FRs and DPs are described in successively more detail. The zigzagging process is depicted schematically in Figure 3.2 which is very similar to Figure 3.1, however arrows have been added between the domains to indicate the iterative mapping at each consecutive level. At the higher levels the descriptions are usually quite general or conceptual in nature. At the lower levels the DPs generally contain a detailed enough description of a given physical solution for implementing the proposed approach[10].

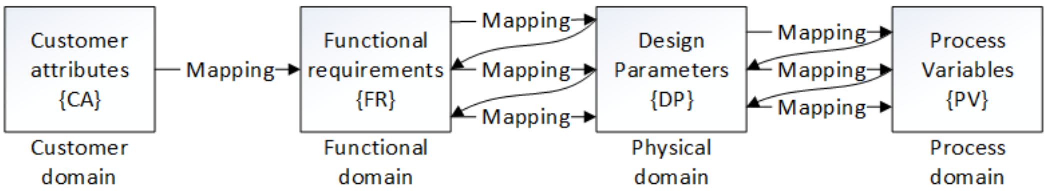


Figure 3.2: Axiomatic Design domains and zigzag mapping between domains

At each level, once the designer has worked out a set of FRs and countered them with appropriate DPs, the designer, governed by the Axioms, evaluates the quality of the selected parameters in order to optimize the design [11].

Although this process of zigzagging seems most adept to the relationship between FRs and DPs, but mapping can also be done between the DPs and PVs [12].

3.1.3 Mathematical Representation of Axiomatic Design

The Axiomatic Design domains can be represented as vectors and matrices, the relationship between the FRs and the DPs is the Design Matrix. The mapping process previously described in Section 3.1.2 can be described mathematically with Equation 3.1.

$$\{FR\} = [A]\,\{DP\} \tag{3.1}$$

Where $[A]$ represents the Design Matrix. For an n sized Design Matrix, the relationship can be presented in an expanded form showing the respective elements of the DM, as shown in Equation 3.2

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ \vdots \\ FR_n \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & \dots & A_{1n} \\ A_{21} & A_{22} & \dots & A_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A_{n1} & A_{n2} & \dots & A_{nn} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ \vdots \\ DP_n \end{Bmatrix} \tag{3.2}$$

The FR and DP vectors, as well as the Design Matrix can be of any size required.

3.1.3.1 Design Coupling

The DM can take any form depending on the relationship of the DPs to the FRs. By applying the Independence axiom to the DM it is possible to evaluate if the the FR can satisfy the DPs independently of each other. Based on this independence it is possible to differentiate between three types of designs as determined by the form of the DM. Two forms are however of special note as they satisfy the Independence axiom.

Uncoupled Design For a diagonal Design Matrix the FRs are satisfied by their respective DPs independently of the others, this is known as an uncoupled design. This means that any design changes made to factors effecting a FR and DP pair will affect that pair only, therefore the designer can safely make the required changes without fear of having to redesign or change any other aspect of the design. An example of a DM for an uncoupled design can be seen in Equation 3.3.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ \vdots \\ FR_n \end{Bmatrix} = \begin{bmatrix} x & 0 & \dots & 0 \\ 0 & x & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & x \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ \vdots \\ DP_n \end{Bmatrix} \tag{3.3}$$

Decoupled Design A design with a triangular DM is known as a decoupled design. If the DM is triangular the independence of the FRs is only assured if the order of the DPs is correct, this is true for both upper and lower triangular matrices. This means that a designer can make a change to a part of the design but successive pairs of DPs may have to be revised due to a change in the other affecting it's design. An example of a Design Matrix for a decoupled design can be seen in Equation 3.4.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ \vdots \\ FR_n \end{Bmatrix} = \begin{bmatrix} x & 0 & \dots & 0 \\ x & x & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ x & x & \dots & x \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ \vdots \\ DP_n \end{Bmatrix} \tag{3.4}$$

Coupled Design Any design that yields a Design Matrix that is non-diagonal and non-triangular is known as a coupled design and the DM is referred to as a full matrix[6]. Such a design is unable to fulfil the Independence Axiom meaning that a change in one DP will always affect some or all of the others. An example af such a matrix can be seen in Equation 3.5.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ \vdots \\ FR_n \end{Bmatrix} = \begin{bmatrix} x & x & \dots & x \\ x & x & \dots & x \\ \vdots & \vdots & \ddots & \vdots \\ x & x & \dots & x \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ \vdots \\ DP_n \end{Bmatrix} \tag{3.5}$$

3.1.4 Constraints

Some aspects of the customer's requirements carries information that while is not fit for adaptation as an FR, does nonetheless constitute an important design consideration and can potentially decide whether the design meets the CNs or not. Somehow this information needs to be collated and used to evaluate the proposed design.

In Axiomatic Design theory there exists the concept of Constraints (Cs) which is used to define limits on the design without specifying how the limits shall be achieved. The Constraints are defined at the same time as the top level Functional Requirements, using the CNs. The Cs can affect one ore more aspects of the design and be valid at multiple design levels [7].

For example, in building a design the designer could use a FR to define criteria for the design of a beam, for example its capacity, stiffness, or material selection. The designer could however also employ Constraints to define the maximum acceptable cost for each linear unit of the beam. Two types of beams can therefore fulfil the FRs , those that meet the Constraints, and those which don't. While both designs will provide the functionality desired, only one will do so at an acceptable price.

Constraints are not solely used for placing cost limits on a design, but usually always consist of a hard limit.

Chapter 4

Design

4.1 Application of Axiomatic Design

Applying the Axiomatic design framework as described in Section 3.1 starts by gauging the Customer's Needs. Only once the designer has understood what the customer requires can the design process begin.

4.1.1 Customer needs

In the case of the SureTrack bin we can use the information set forth in Chapter 2 to describe the needs of the customer. As discussed in Chapter 1 the current version of the SureTrack transfer bin fulfils its purpose, however the current design is considered expensive and is prone to fatigue cracking. These two facts along with the necessary considerations of what the bin is supposed to accomplish should it be used in a transfer system can be used to list the following design considerations.

Using this information we can form the statement of the customers needs, we know that the customer would ideally would like a stronger bin at a lower price or at least a less expensive but equally strong bin, additionally it should be possible to use the bin in some form of transfer system as mentioned in Section 1. The formal statement of the customers needs would be:

> **CN0 -** A transfer bin for whole salmon, compatible with the SureTrack grader, cheaper and less prone to cracking due to skewing. The bin should be adaptable to a pure transfer task and be able to discharge anywhere along it's path, accidental discharge shall be prevented.

4.1.2 Base level requirements

With the CNs formalized the designer's task is to map the CNs statement to an FR in the Functional Domain and thereby "define the overall objective of the decomposition" [13]. Upon reading and dissecting the information contained in the CN it's evident from the CNs that the basic requirement of the bin is to transfer whole salmon, any other demands made of the bin are secondary, however important enough to determine if the design is usable or not. The meaning of the previous statement is that a perfect bin with an extremely low production cost and nearly unlimited strength is unusable if the bin is not able to transfer the product. The statement of the base level FR thus becomes:

FR0 - Transfer whole salmon.

The designers task at this point is mapping the information in the Functional Domain to the Physical domain and in doing so, defining how the Functional Requirements shall be realized. The information used in the formulation of the base level Design Parameter is drawn from both previous statements of the CN's and FR's, but additionally from the knowledge gleaned from the background information on the current design. Thus the statement of the base level Design Parameter becomes:

DP0 - Transfer bin for whole salmon, redesigned for cost and strength.

4.1.3 Refining the requirements

Having established the base level FR and DP pair, the decomposition of this base level pair as described in Section 3.1.2.1 can commence. Analysing the base level FR of "Transfer product" it's trivial to realise that the act of transferring a product can be split into the FRs of containing the product once it's been fed into the bin, moving the product, and discharging the product once it's been moved to the appropriate location. The FRs are then mapped to DPs, the product is contained within the main weldment of the bin, the product is discharged by the discharge system and the product and bin are moved by the support system. This results in the top level FRs and associated DPs listed in Table 4.1

Table 4.1: Top level FR-DP pair.

Element	Functional Requirement	Design Parameter
1	Contain product	Main weldment
2	Move product	Support system
3	Discharge product	Discharge system

Applying the Independence Axiom to the top level FR-DP pairs the Design Matrix of Equation 4.1 can be constructed.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} x & 0 & x \\ 0 & x & 0 \\ 0 & 0 & x \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \tag{4.1}$$

Each DP is linked to its respective FR, additionally FR_1 is linked to DP_3. The reasoning for this connection is that the product can obviously not be contained unless the discharge system is in a closed position, should it come open during the transfer of the product the DP associated with product containment is not the only one governing the FR. The top level Design Matrix is an upper triangular matrix, therefore the design is decoupled as described in Section 3.1.3.

The following Constraints need to be placed on the design of the bin to make it compatible with the SureTrack grader.

Table 4.2: Top level Constraints.

Element	Constraint
1	Center distance of wheels shall be 940 mm.
2	The support pin shall have a diameter of 20 mm where it meets the drive chain and be appropriately sized for a chain centre to centre span of 1099 mm.
3	Maximum width of the bin, excluding the support system shall not exceed 950 mm.

With the top level FRs and DPs, as well as the Constraints obtained, the decomposition can be continued to the next level with the further refinement of the first DP. For the first FR the bin needs to contain not only a single fish, but on the outfeed side of the SureTrack grader it needs to be able to carry a batch of fish up to $12,5\ kg$, additionally the main weldment defined as DP_1 needs to provide mounting for the support and discharge systems, so those become FRs number 2 and 3, respectively. Lastly the risk of the bin failing due to fatigue shall be decreased. Using this information, Table 4.3 is populated.

Table 4.3: FR1 decomposition.

Element	Functional Requirement	Design Parameter
1	Contain product batch	Volume > $25\ l$
2	Support the support system	Support system mounts
3	Support the discharge system	Discharge system mount
4	Decrease risk of fatigue failure	Reduce joint stress

Applying the Independence Axiom to the above FR-DP pairs the Design Matrix in Equation 4.2 can be constructed.

$$\begin{Bmatrix} FR_{1.1} \\ FR_{1.2} \\ FR_{1.3} \\ FR_{1.4} \end{Bmatrix} = \begin{bmatrix} x & x & 0 & 0 \\ 0 & x & 0 & 0 \\ 0 & 0 & x & 0 \\ 0 & 0 & 0 & x \end{bmatrix} \begin{Bmatrix} DP_{1.1} \\ DP_{1.2} \\ DP_{1.3} \\ DP_{1.4} \end{Bmatrix} \tag{4.2}$$

For $FR_{1.1}$ the first Constraint in Table 4.2 is applicable. The width of the bin is limited by the fact that it must fit inside the frame of the SureTrack grader.

The decomposition of the FRs continues with further examination of FR_2 as it can be further broken down into the facts that we would like the transfer bin to maintain its orientation no matter in which direction it is travelling, additionally there is a force acting on the bin to open it during its horizontal travel. Therefore it makes sense to split this into two separate FRs as per Table 4.4. In order to allow for the bin to rotate freely during the portions of vertical travel of the track the bin must be able to rotate freely about an axis with an offset to prevent the bin from tipping over. For the horizontal portion of travel the bin must be able to travel without any rotation at all, even during the contact with the actuation mechanism of the discharge system, this force can be countered with moment negating wheels.

Table 4.4: FR2 decomposition.

Element	Functional Requirement	Design Parameter
1	Rotate freely during vertical motion	Support pin
2	Maintain constant orientation during hor. motion	Moment countering wheels

Applying the Independence Axiom to the above FR-DP pairs the Design Matrix in Equation 4.3 can be constructed.

$$\begin{Bmatrix} FR_{2.1} \\ FR_{2.2} \end{Bmatrix} = \begin{bmatrix} x & 0 \\ 0 & x \end{bmatrix} \begin{Bmatrix} DP_{2.1} \\ DP_{2.2} \end{Bmatrix} \tag{4.3}$$

The support pin of $DP_{2.1}$ is restricted by Constraint 2 in Table 4.2 as the support pin of the redesigned bin must appropriately interface with the drive chain of the SureTrack grader.

The location and moment countering wheels of $DP_{2.2}$ are limited by Constraint 3 in Table 4.2 as the wheels must fit the track of the SureTrack grader.

The third top level FR is decomposed in a manner identical to the previous ones. It is clear that we want the product only to discharge when it's called for, therefore we need to employ some sort of locking mechanism. Secondly for the sake of a transport system we want it to be possible to discharge the contents of the bin irrespective of the travelling direction, i.e. whether it's travelling on the upper tier or the lower tier, therefore we specify that the actuation of the discharge system should be in the vertical direction. Lastly we want to ensure a full discharge of the bin and for that reason it's necessary to ensure the opening area of the discharge system is sufficient.

Table 4.5: FR3 decomposition

Element	Functional Requirement	Design Parameter
1	Discharge only where specified	Locking mechanism
2	Discharge while travelling horizontally	Vertical actuation of discharge system
3	Promote full discharge	Discharge area

Applying the Independence Axiom to the above FR-DP pairs the Design Matrix in Equation 4.4 can be constructed.

$$\begin{Bmatrix} FR_{3.1} \\ FR_{3.2} \\ FR_{3.3} \end{Bmatrix} = \begin{bmatrix} x & x & 0 \\ 0 & x & 0 \\ 0 & 0 & x \end{bmatrix} \begin{Bmatrix} DP_{3.1} \\ DP_{3.2} \\ DP_{3.3} \end{Bmatrix} \tag{4.4}$$

At this point the design has been decomposed to the decisive factors affecting the design. The FR and DP pairs along with their respective DMs can be compiled as shown in Equation 4.5, showing the total relations between all the Functional Requirements and Design Parameters.

$$\begin{Bmatrix} FR_{1.1} \\ FR_{1.2} \\ FR_{1.3} \\ FR_{1.4} \\ FR_{2.1} \\ FR_{2.2} \\ FR_{3.1} \\ FR_{3.2} \\ FR_{3.3} \end{Bmatrix} = \begin{bmatrix} x & x & 0 & 0 & 0 & 0 & x & 0 & 0 \\ 0 & x & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & x & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & x & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & x & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & x & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & x & x & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & x & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & x \end{bmatrix} \begin{Bmatrix} DP_{1.1} \\ DP_{1.2} \\ DP_{1.3} \\ DP_{1.4} \\ DP_{2.1} \\ DP_{2.2} \\ DP_{3.1} \\ DP_{3.2} \\ DP_{3.3} \end{Bmatrix} \tag{4.5}$$

An addition has been made to the total Design Matrix to account for the effect of $DP_{3.1}$ on FR_1.

4.2 Preliminary analysis

In order to fulfil the FRs derived in the previous chapter and come up with solutions that are superior to the ones employed by the SureTrack bins design, it's necessary to review each FR-DP pair and analyse how the design can be optimised.

4.2.1 Contain product batch

The DP associated with the FR "Contain product batch" is "Volume" as the bin has to be designed with enough volume to contain the prescribed batch of product. The volume of the original SureTrack bin is just under $31\,\mathrm{L}$, providing enough volume for a $25\,\mathrm{kg}$ Styrofoam (closed cell Polystyrene) box, which have a volume of around $50\,\mathrm{L}$, to be filled by depositing two batches. The redesigned bin should also be able to accomplish this, therefore the total volume of the redesigned bin must not be less than $25\,\mathrm{L}$.

4.2.2 Provide mounting for support system

The system of parts supporting the bin need to be fastened onto the main weldment of the bin, hence the statement of the FR "Interface with support system" and it's respective DP, "Support system mounts". In the case of the SureTrack transfer bin, the support system is a support pin that interfaces with the chain drive of the SureTrack grader and wheels to prevent the bin from tipping when the force of the discharge actuation mechanism is applied to the bin. As the redesigned bin is to be used with the SureTrack grader the part interfacing with the grader can not be changed, but the way they interface with the grader can. Having the support pin removable would allow for the possibility of the discharge system utilising the support pin as a bearing pin and therefore negating the need for welding additional bearing mounts to the main weldment.

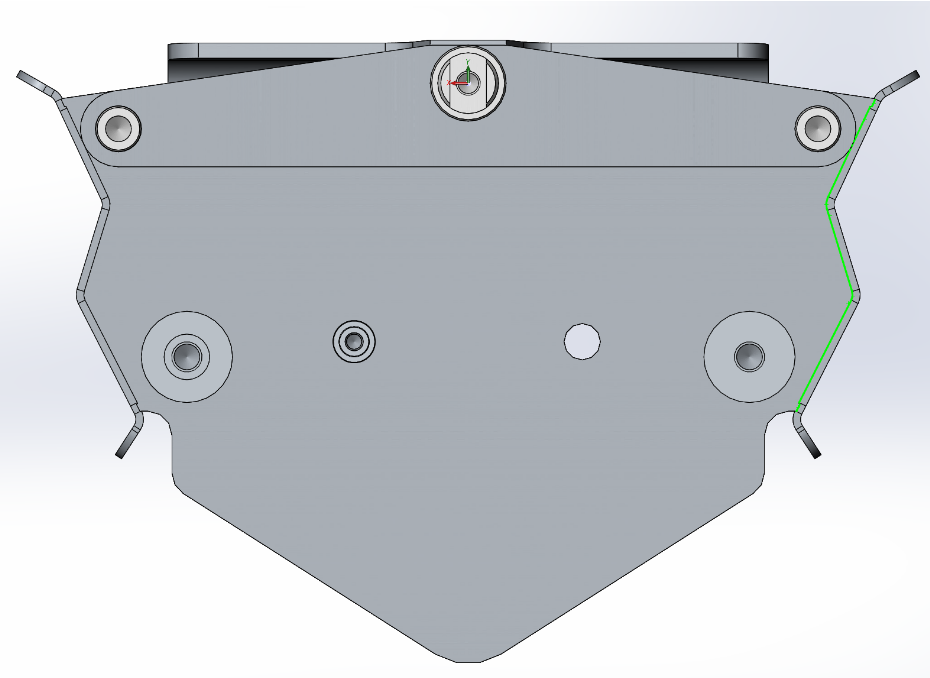


Figure 4.1: Total length of the weld joining the long sides to the gable ends of the SureTrack bin.

4.2.3 Provide mounting for discharge system

The discharge system needs to be mounted to the bin's main weldment as indicated with the FR "Interface with discharge system" and its associated DP "Discharge system mounts". As the support pin that interfaces with the chain drive of the SureTrack grader must be centrally located on the gable end of the bin, it's ideally suited for providing the rotational axis that the doors of the discharge system rotate about. For this implementation to be feasible the support pin must be removable.

4.2.4 Increase skewing resistance

The DP associated with the FR "Increase skewing resistance" is "Anti-skewing stiffening". This stiffening can be realised in any number of design features, including an extended weld area, stiffeners or outriggers relieving the joint of the moment induced by the skewing motion or a joint with a higher inertia moment. As this is the factor most reported having problems it would be practical to implement as many of these countermeasures as possible.

As shown in Figure 4.1 the weld joining the gable ends and the long sides of the SureTrack bin is "s" shaped, presumably to increase the strength of the long side itself as well as strengthen the welded joint. The total length of the joint is $109\,\mathrm{mm}$. The maximum displacement of the welded joint is $26\,\mathrm{mm}$, measured along the x-axis as shown in Figure 4.2.

By designing the bin in such a manner, the welded joint is both lengthened and its displacement increased to increase the inertia moment, the joint could be strengthened. An important factor affecting the geometry of the main weldment is the constraint placed on the redesign by the geometry of the SureTrack grader, as it is vital that the redesigned bin must fit the space allowed for the original SureTrack bin.

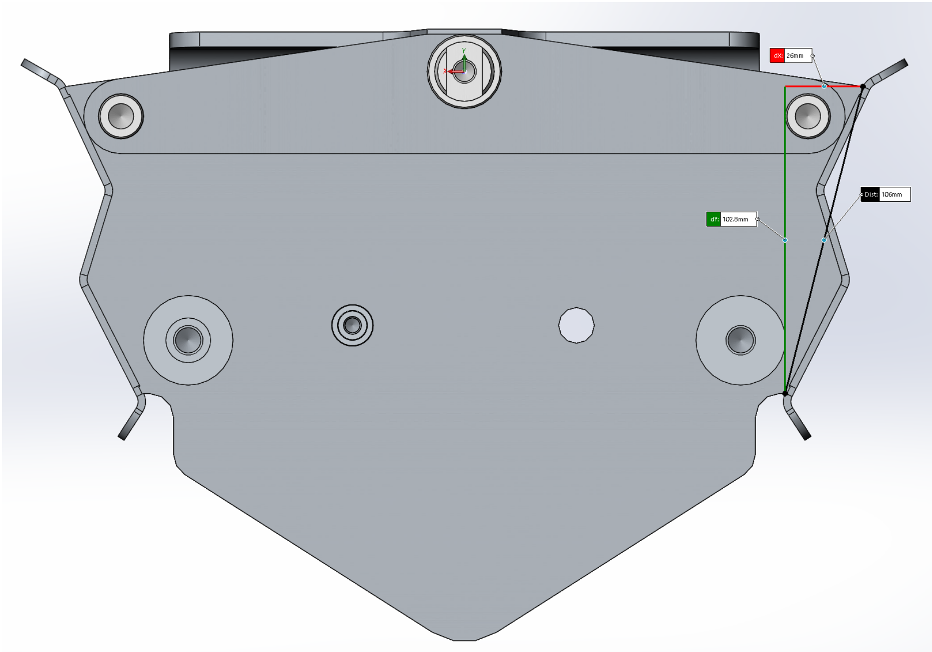


Figure 4.2: Effective width along the x-axis (26 mm) of the weld joining the long sides to the gable ends of the SureTrack bin.

4.2.5 Rotate freely during vertical motion

The bin must be prevented from rotating during horizontal travel as per $FR_{2.2}$, however during any non horizontal travel the bin must be free to rotate so as not to tip over as the drive chain traverses its path around the SureTrack grader. This rotation is best implemented where the support pin meets the drive system of the grader as this calls for no changes to be made to the grader, this is governed by $C_{2.1}$. Therefore the end of the support pin mating with the drive system needs to stay unchanged. This does not however interfere with the proposed dual function of the support pin that is described in Section 4.2.3 as the end of the support pin that mates with the bin itself can be adapted to this task. Pictured in Figure 4.3 is the support pin of the SureTrack bin, note the shoulder of the pin and the non-rotating laser cut washer, where in between the rotating connection with the chain drive is made.

4.2.6 Maintain constant orientation during horizontal motion

The DP associated with the FR "Constant orientation during horizontal motion" is "Moment countering wheels". The reason that this is important concerns both the charging and discharging of the bin. Should the bin the rocking when being charged with product the possibility of the product hitting the sides of the bin and sliding off is real and the grader having no means to realise this would create batch that is too small. Although the batch would be discarded during check weighing the problem must still be addressed. Another factor concerning the necessity of countering the bins rotation is the turn over risk created by the discharge of the bin. As is evident by the actuation of the discharge mechanism in the SureTrack bin moment is created about the support pin. The moment is created when the discharge actuation mechanism of the SureTrack grader contacts the discharge system of the SureTrack bin. This moment needs to be countered in order for the bin to stay in its upright position while travelling horizontally, in the original SureTrack bin this is handled using two wheels on each side of the bin, for a total of four wheels per bin. Due to the limitation im-

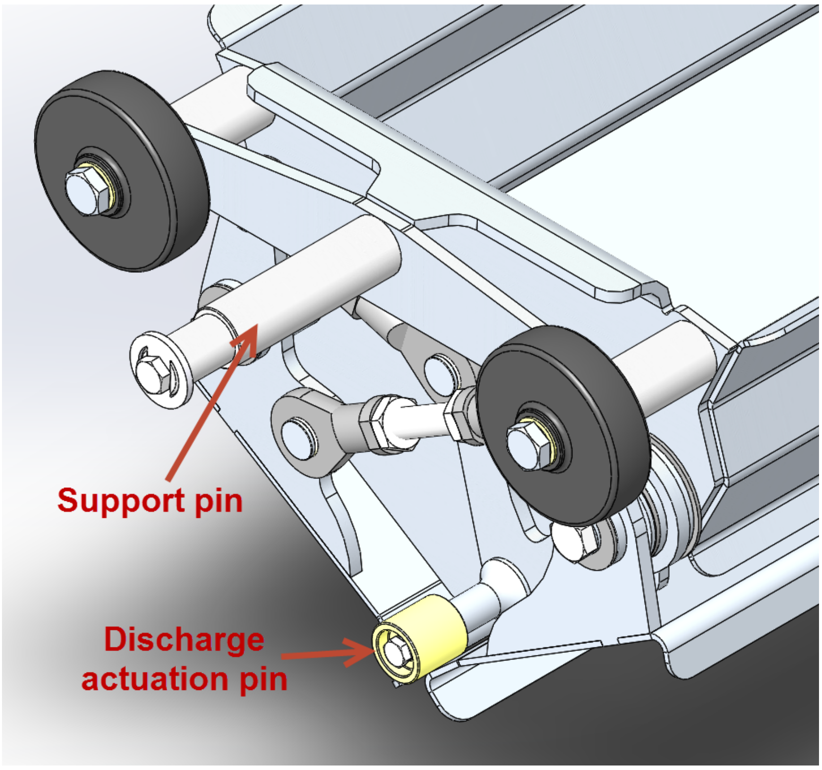


Figure 4.3: Support pin of the SureTrack bin.

posed by the backwards compatibility of the redesigned bin with the SureTrack grader itself, this method needs to be used for the redesigned bin as well. Should the SureTrack grader be redesigned, or the bin used in another machine, one wheel could be omitted in favour of a track in the machine on both sides of the wheels. This could be done without changing the design of the redesigned bin.

4.2.7 Discharge only when intended

To fulfil the FR “Prevent accidental discharge” it is necessary to ensure that the bin is locked and not just closed. Therefore the “Locking mechanism” DP is defined. The locking mechanism is however dependent on the design of the discharge mechanism itself as indicated by the relation between $FR_{3.1}$ and $DP_{3.2}$ in the total DM shown on page 23. Technically this could be achieved by having a two step activation of the discharge system. With the first step, or amount of actuation, the lock would be disengaged. By increasing the level of actuation to the second step the discharge would be activated. For this purpose some sort of sliding joint could be employed. By integrating the lock in the discharge mechanism in such a manner that the lock is disengaged using the same force as the actuation of the discharge mechanism, considerable savings in production cost could presumably be achieved with such a design due to the consolidation of parts. Both parts belonging to the bin itself, but the discharge actuation mechanism on the SureTrack grader as well.

4.2.8 Discharge in either horizontal direction

In order to fulfil the FR “’Discharge while travelling horizontally” the DP “Vertical actuation of discharge system” was defined. With the actuation mechanism of the discharge system operated in either vertical direction it’s ensured that the discharging process is independent

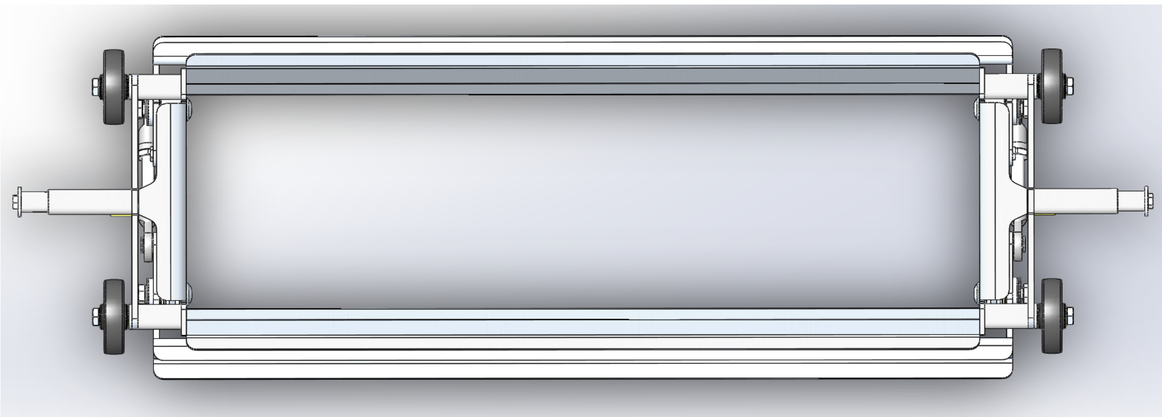


Figure 4.4: The discharge area of the SureTrack bin.

of the travelling direction of the bin. To discharge the bin the discharge actuation mechanism on the SureTrack grader would have to be designed with either symmetry or reversibility in mind in order to be compatible with this bi-directional discharge.

Although the DP states that the actuation direction of the discharge system should be vertical it will be in the upwards direction. The task of reversing the force within the discharge mechanism is impractical, additionally with the upward discharge actuation the bin would be closed by its own weight after the discharge is complete and not require an external force to close.

4.2.9 Promote full discharge

The DP associated with the FR “Insure full discharge” is “Discharge area”, meaning that the discharge area of the bin must be large enough to ensure a full discharge in a sufficiently short amount of time when called for. The SureTrack bins boxy construction makes for a discharge area of $0,18\ m^2$ which is nearly identical to the input area of the bin as shown in Figure 4.4, where the view is from the top looking down through the SureTrack bin. The discharge area of the SureTrack bin has proven to be sufficient and provides an accurate and complete discharge. Ideally the redesigned bin should have an equal ejection area to the one of the SureTrack bin. However this will prove complicated due the geometric constraints and call for increased skewing resistance which necessitates dropping the near vertical seam between the bins gable ends and long sides in favour of a joint offering more inertia moment, therefore a discharge area of 60% of that provided by the SureTrack bin will be considered adequate.

4.3 Redesigned transfer bin

With the requirements of the redesign generalised using the Axiomatic Design framework and further decomposed to a level where the requirements could be stated as achievable goals and then analysed further, the task of modelling the bin was undertaken. This was done using the DSS SolidWorks 3d CAD suite.

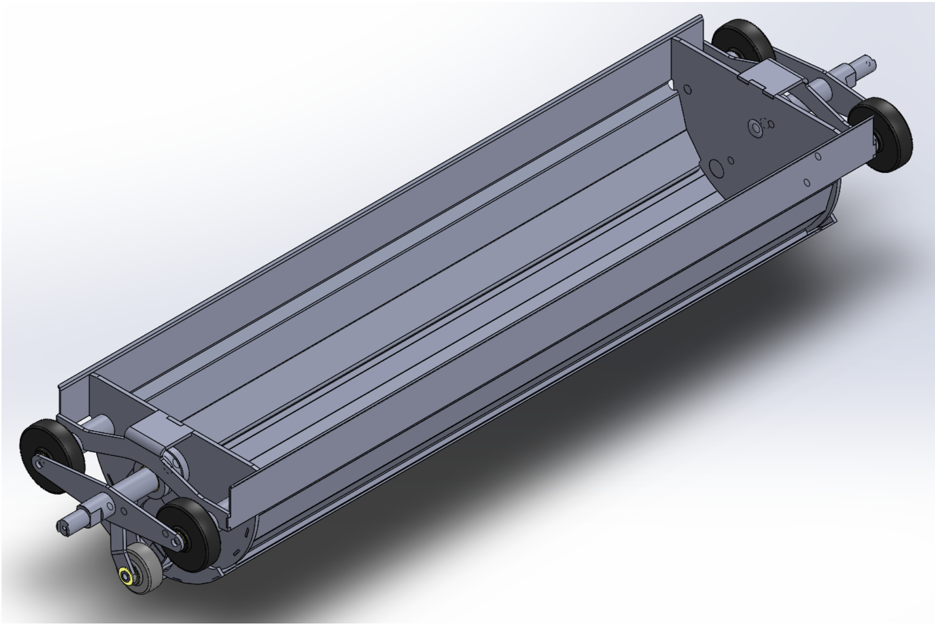


Figure 4.5: The redesigned bin in its closed position.

4.3.1 Summary of the design

The basic theory of the design was that by making the product container of the main weldment round, increased stiffness in the joint between the gable ends and the long sides of the bin would be achieved because of a longer and more favourably shaped joint. Adding an outrigger to the support system would further assist in providing increased joint stiffness. Additionally by making the section profile of the bin round, the movement of the discharge system could be rotational, thus enabling the use of the support pin as the rotational axis. For a discharge system of a semi-round profile the locking and actuation system employed by the original SureTrack bin were unpractical so a discharge system was devised where a simple upwards force from a ramp or cam based discharge actuation mechanism located on the SureTrack grader would trigger the discharge mechanism. Additionally the discharge system was refined to be positively locked unless when activated. The release of the lock is triggered with the same motion as the actuation of the discharge system. As the redesigned bin is meant to be able to be substituted for the SureTrack bin in current machinery it bears geometric similarities to the SureTrack bin. The redesigned bin is illustrated in Figures 4.5 and 4.6 with the discharge mechanism in the closed and open position respectively.

The redesigned bin measures $1132\,\mathrm{mm}$ in length, by $245.6\,\mathrm{mm}$ in width, and $204.9\,\mathrm{mm}$ in height. The weight of the bin excluding fasteners is $16.56\,\mathrm{kg}$. The distance between chain mount centrelines is $1099\,\mathrm{mm}$. The centre distance between the wheels of the support system is $940\,\mathrm{mm}$.

The redesigned bin is made up of custom made parts and purchased standard items. The custom parts are machined steel and polymer parts in addition to laser cut and bent sheet metal. All steel is 1.4301 stainless steel. The purchased parts are standard bolts, nuts and washers for assembly and bearings manufactured by IGUS. The type and number of parts that make up the redesigned bin are listed in Table 4.6.

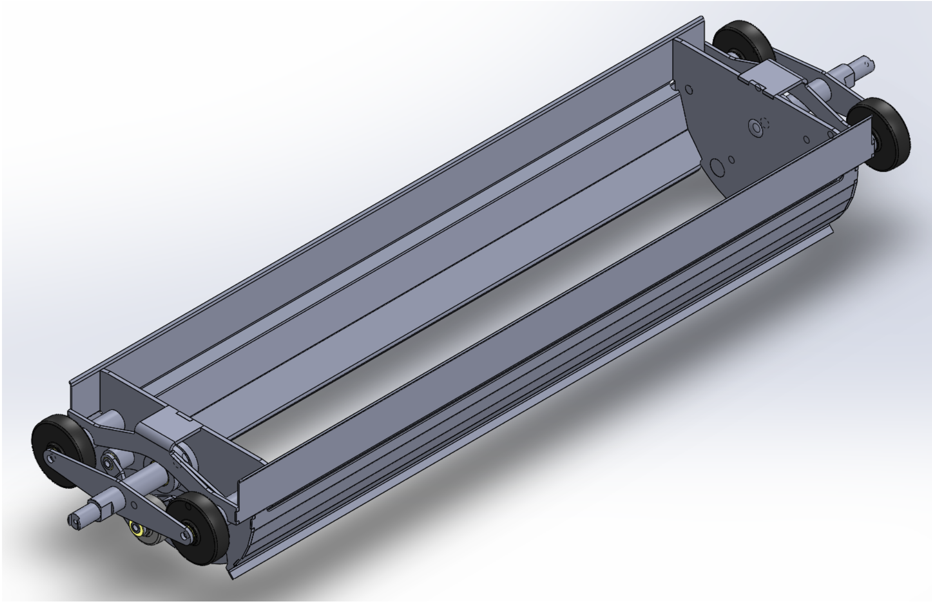


Figure 4.6: The redesigned bin in its open position.

Table 4.6: Redesigned locked bin part count.

Element	Sheet steel	Turned & milled	Purchased†	Total part count
Main weldment	6	8	0	14
Support system	2	6	8	16
Discharge system	12	16	18	46
Total	20	30	26	76

† Purchased items does not include standard bolts and washers.

As the original SureTrack bin, the redesigned bin is divided into three primary elements, The main welded assembly or weldment, the support system and the discharge mechanism. These elements are illustrated in Figures 4.7 and 4.8, where the main weldment is coloured red, the support system is coloured green and the discharge system is coloured blue.

4.3.2 Main weldment

The main weldment of the redesigned bin serves the same purpose as in the SureTrack bin, it's an integral part of the bin itself, forming the four sides of the container section of the bin and serves as a backbone for mounting of the support system and discharge system to the welded bearing points.

As seen in Table 4.6 the main weldment is constructed from 6 sheet metal components and 8 machined components. The sheet metal components are three identical pairs. One pair has a single bend, forming the side braces. The second pair as 5 bends forming the long sides and the third pair is not bent and makes up the gable ends. The arrangement of the sheet metal items is illustrated in Figure 4.9. The brace added to the sides of the main weldment serves two purposes, firstly it adds support to the mounting points for the support system and secondly it connects to the long sides of the bin to stiffen the bin against skewing from unequal loads.

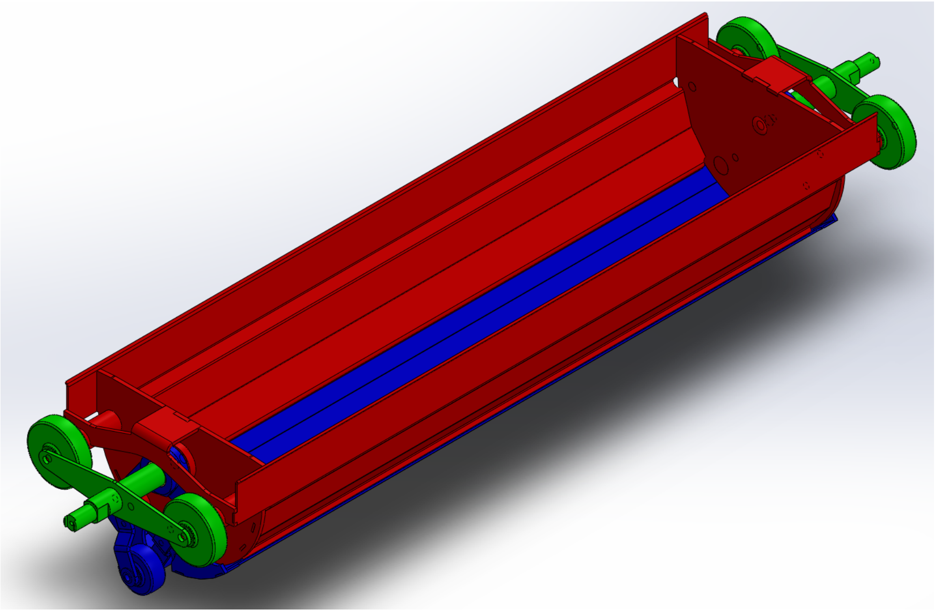


Figure 4.7: The redesigned bin elements, bin in closed position. Main weldment is coloured red, support system is coloured green and the discharge system is coloured blue.

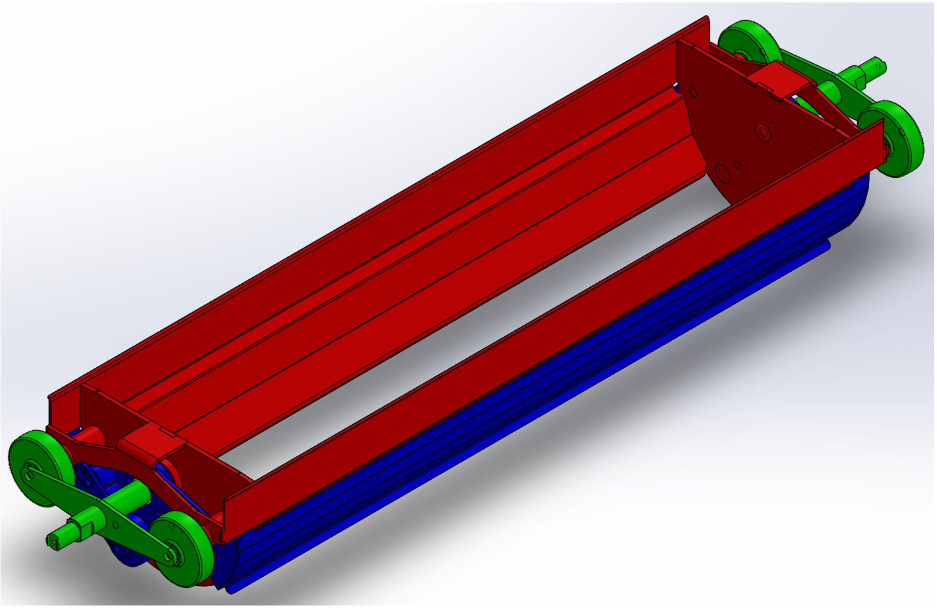


Figure 4.8: The redesigned bin elements, bin in open position. Main weldment is coloured red, support system is coloured green and the discharge system is coloured blue.

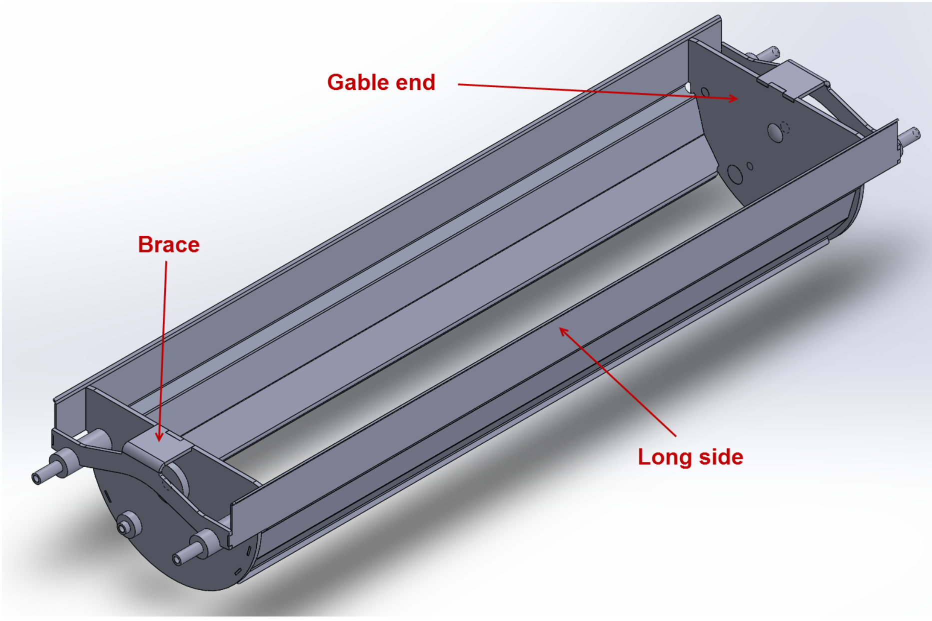


Figure 4.9: Isometric view of the redesigned bin main weldment illustrating the sheet metal components of the main weldment.

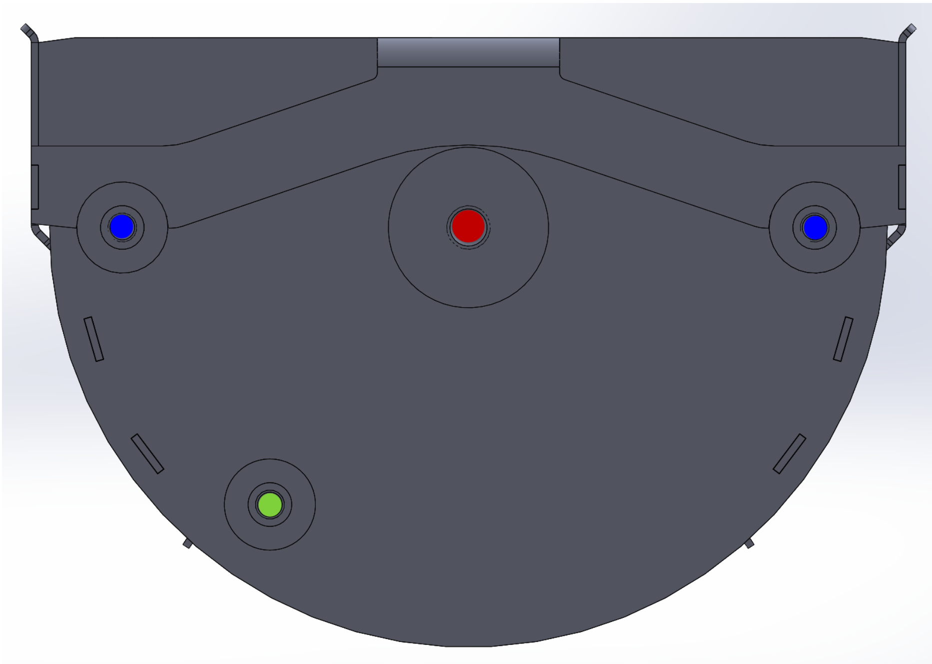


Figure 4.10: Side view of the redesigned bin main weldment illustrating the mount points of the main weldment.

The machined components of the main weldment form mounting points, four on each side of the main weldment. The mounting points are used to attach the support system and discharge system. In Figure 4.10 these mounting points are illustrated. The central red dot indicates the mounting point for the main bearing pin that connects to the chain drive, this mount point also doubles as the pivot point for the discharge systems doors. The blue dots indicate the mounting points for the wheels of the support system. The green dot indicates the mount point for the steering link of the discharge system.

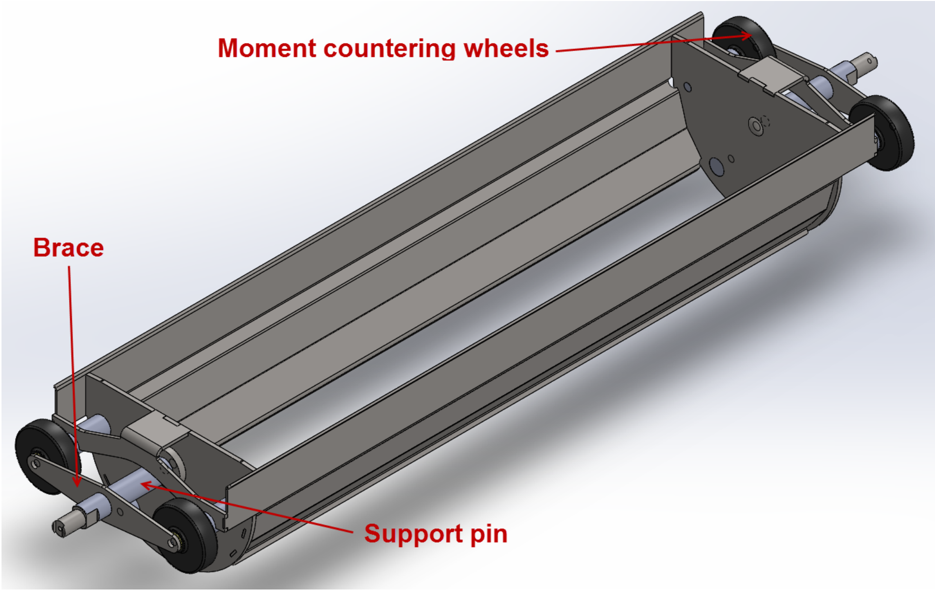


Figure 4.11: The redesigned bin support system and main weldment. The central red dot indicates the mounting point for the main bearing pin that connects to the chain drive, this mount point also doubles as the pivot point for the discharge systems doors. The blue dots indicate the mounting points for the wheels of the support system. The green dot indicates the mount point for the steering link of the discharge system

4.3.3 Support system

The support system of the redesigned bin nearly identical to the one on the SureTrack bin, POM wheels with IGUS bearings. The support system shown in Figure 4.11 is constructed from 2 sheet metal components, 6 machined components and 8 purchased items as indicated in Table 4.6. The sheet metal items are an identical pair of unbent braces, the purpose of the braces is to add additional strength to the removable bearing pin, the braces like the bearing pin are removable. The machined components are the POM wheels, and the bearing pin itself.

The redesigned support system differentiates from the original SureTrack design in two ways. Firstly the bearing pin is a part of the support system and is removable to facilitate the assembly and disassembly of the bin. Secondly because the bearing pin is removable a brace is added to support the bearing pin. The wheels of the support system are constructed in an identical manner as in the SureTrack bin.

4.3.4 Discharge system

The discharge system is where the redesigned bin differs the most from the original SureTrack design. Whereas the the SureTrack design dumps the contents of the bin by dropping the doors of the discharge system, the doors of the discharge system of the redesigned bin have to be rotated upwards in order to discharge its contents. The doors of the redesigned discharge system rotate in IGUS bushings about the support pin of the support system.

The discharge system is equipped with a wheel of similar design to the wheels of the support system but of smaller diameter. The purpose of the wheel is to act as a cam follower once it engages the actuation mechanism of the SureTrack grader. The actuation mechanism could be cam or ramp shaped, the important aspect is that it must provide lift under the

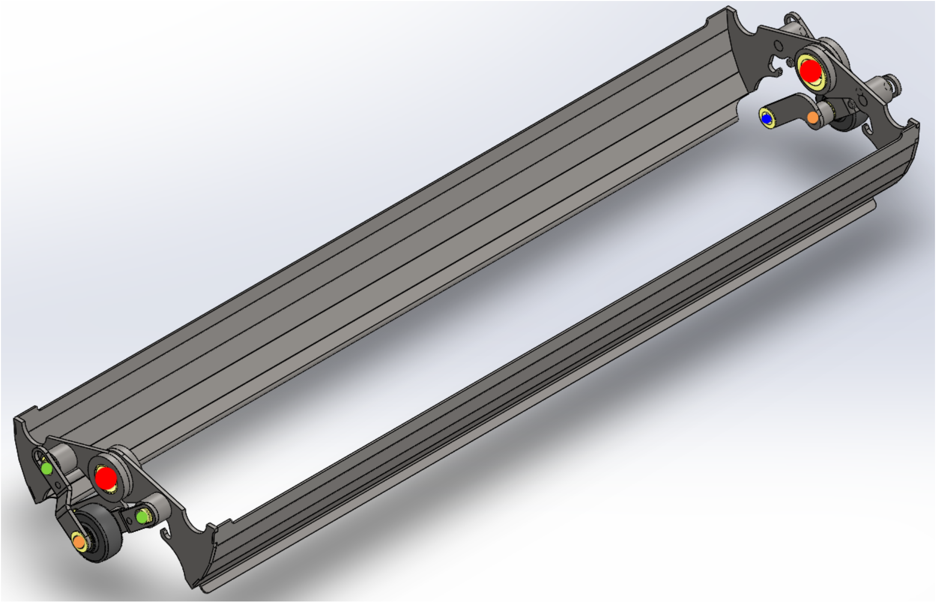


Figure 4.12: The redesigned bin discharge system in its closed position.

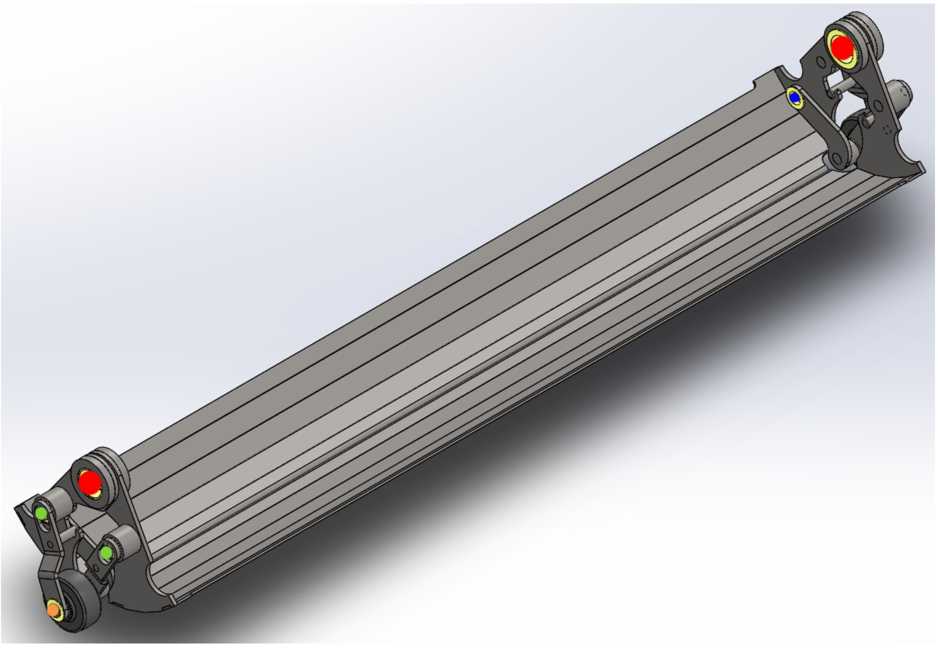
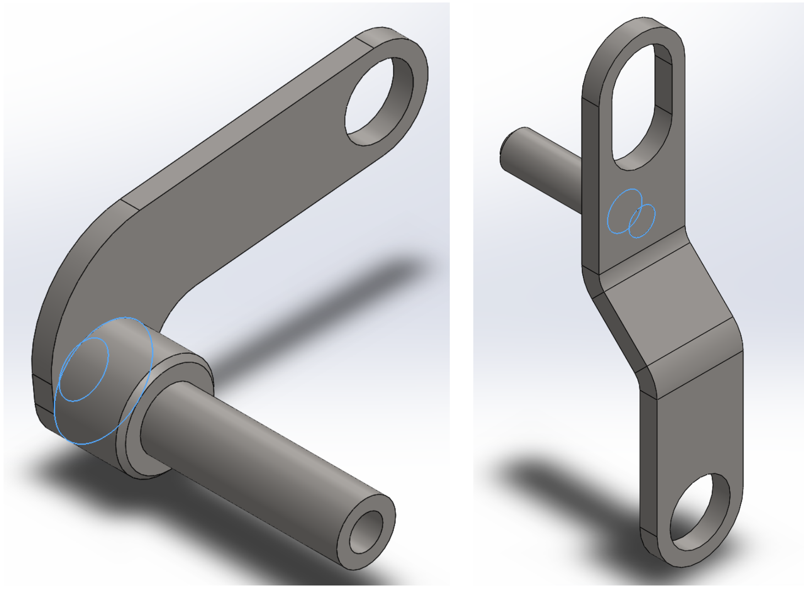


Figure 4.13: The redesigned bin discharge system in its open position.

wheel. The lift is what activates the discharge mechanism, first unlocking the discharge doors and secondly providing the moment required to open the doors.

The discharge system is pictured in its entirety, with the main weldment and support systems removed for clarity, in Figures 4.12 and Figure 4.13 in its open and closed positions respectively. In the figures the pivot point for the discharge system is indicated with a red dot, similarly the green dots indicate the pivot points of the opening links on the discharge doors. The blue dots indicates the pivot point of the guide link, lastly the orange dot indicates the rotational axis of the wheel of the discharge system.

As seen in Table 4.6 the discharge system is constructed from 12 sheet metal components, 16 machined components and 18 purchased items. The sheet metal components make up the doors, containing 3 individual sheet metal pieces each and the six links of the dis-



(a) The redesigned bin guide link.

(b) The redesigned bin opening link.

Figure 4.14: The links of the redesigned bin discharge system.

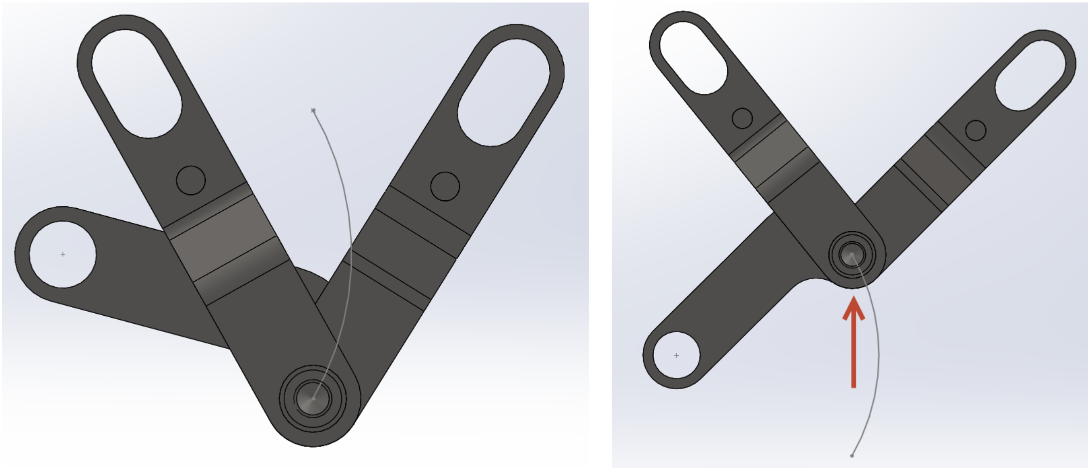
charge system. The machined components comprise bearing holders, link mount points, discharge activation wheel, which is identical to the wheels of the support system, the axle for the activating wheel and the locking pins. The purchased items are IGUS bearing for the links, wheels and doors.

4.3.4.1 Discharge system linkages

In order to activate the doors of the discharge system using vertical motion, linkages connecting the doors to the wheels were required. Three types of linkages were designed, two that provide the connection from the wheel of the discharge system, these links are called opening links. The third link connects the wheel with the main weldment of the bin, this link is called the guide link.

The purpose of the opening links, pictured in Figure 4.14b, is to transfer the vertical motion from the wheel as it traverses the actuation mechanism of the machine in question to the doors of the discharge system, thus providing the force necessary to lift the discharge doors. The opening link is a welded assembly consisting of a sheet metal item and standard stock $8\ mm$ pin. The pin protrudes from one side of the link (alternate sides in each pair) and provides the locking of the discharge system as it interfaces with the sides of the doors of the discharge system. This locking interface can be seen in Figure 4.16b, where the pin rests in the cut out provided in the discharge system door side. One end of the opening link connects with the axle of the discharge system wheel, the other end rides in an oblong hole to provide for the two step activation of the discharge system to facilitate the locking system described in Section 4.3.4.2.

The guide link was added to provide guidance for the actuation of the discharge system. Without the guide link the whole discharge system could possibly rotate about the axis of the support pins when the wheel of the discharge system comes into contact with the actuation mechanism. To prevent this and ensure that the motion of the wheel is vertical is the purpose of the guide link. Because of the radial nature of the connection provided by the guide link



(a) The redesigned bin discharge system linkages in their closed position.

(b) The redesigned bin discharge system linkages in their open position.

Figure 4.15: Discharge system linkages.

between the wheel of the discharge system and the main weldment, the movement of the wheel will always be in the shape of an arc. The radius of which corresponds to the distance from the centre of the main weldment pivot to the centre of the wheel, as shown on Figure 4.15, where the links are displayed in the closed and locked, and the fully open position of the discharge system, in Figure 4.15b, the force from the actuation mechanism of the grader is depicted by a red arrow. Although the path traversed by the wheel is the shape of an arc, the net displacement of the wheel is vertical, as the fully open point is positioned directly above the fully closed point.

The guide link itself is a welded assembly of a sheet metal part that forms the radial link and a machined part that forms the axle for the discharge system wheel. The weld used to connect the radial link with the axle are picture in Figure 4.14a.

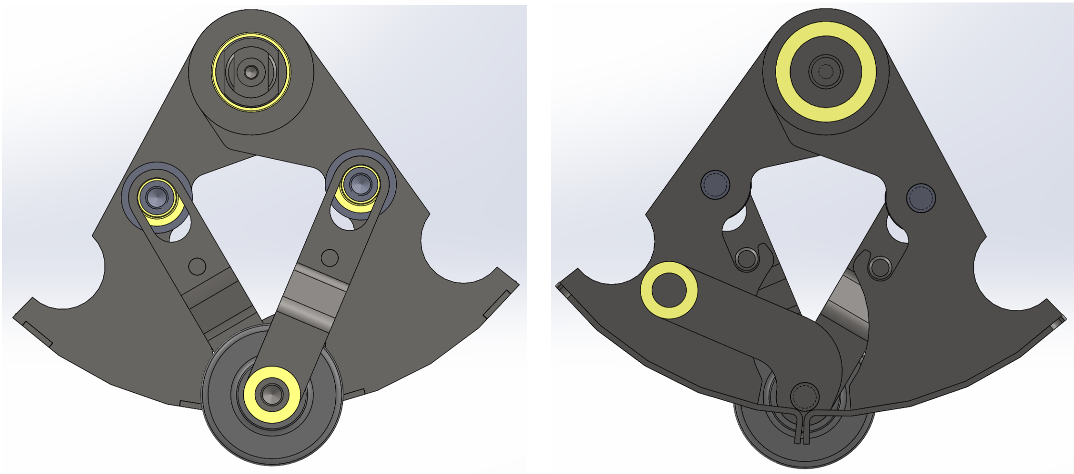
4.3.4.2 Locking system

The bin is equipped with a locking system that is a integrated part of the discharge system. Pins on the linkages described in Section 4.3.4.1 align with slots in the sides of the discharge system doors. The two step nature of the locking discharge system provides for a locked and unlocked position of the linkages before any movement of the discharge system doors occurs. The function of the locking system is as follows.

1. The bin containing product is travelling horizontally. At this stage the discharge system is locked and the wheels and linkages of the discharge system are positioned as shown in Figure 4.16.

2. The wheel of the discharge system traverses the first stage of the ramp of the discharge actuation mechanism of the machine. This induces vertical motion of the wheel resulting in the linkages moving to the unlocked position as shown on Figure 4.17.

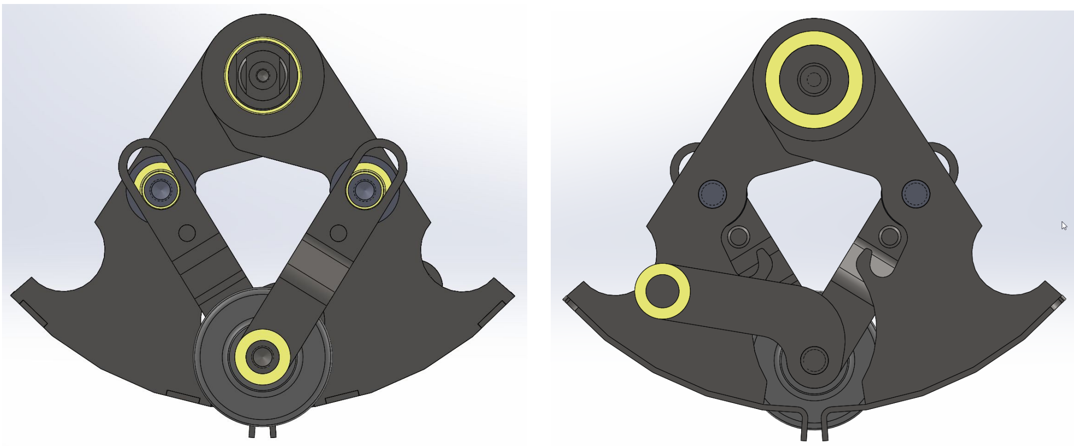
3. The bin continues its horizontal motion and the wheel of the discharge system continues to move vertically. The oblong openings in the opening links to contact the bearing points on the discharge system doors. This causes the discharge doors to rotate about the support pin of the support system and as the doors separate the product



(a) The locking system of the redesigned transfer bin in the locked position as viewed from the outside of the bin.

(b) The locking system of the redesigned transfer bin in the locked position as viewed from the inside of the bin.

Figure 4.16: The locking system of the redesigned transfer bin in the locked position.



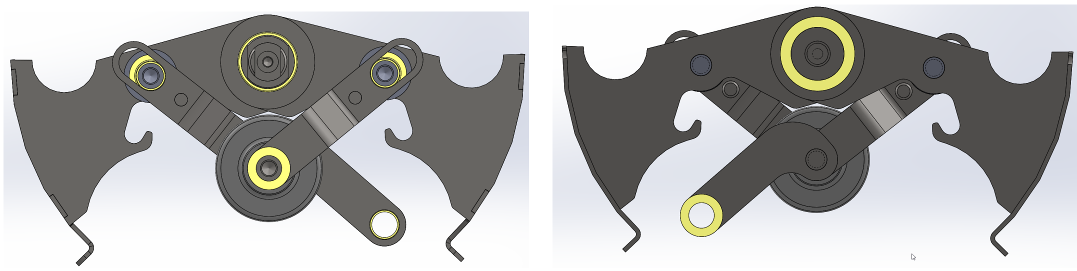
(a) The locking system of the redesigned transfer bin in the unlocked position as viewed from the outside of the bin.

(b) The locking system of the redesigned transfer bin in the unlocked position as viewed from the inside of the bin.

Figure 4.17: The locking system of the redesigned transfer bin in the unlocked position.

is discharged. Once the wheel has been elevated fully by the actuation mechanism of the machine in question the discharge system has the position shown in Figure 4.18.

With the discharge activation mechanisms in its unsupported position the alignment of the pins and slots is such that the bins catch on the pins and cannot open. In order for the pins to clear the slots in the door sides the discharge actuation mechanisms has to activated



(a) The locking system of the redesigned transfer bin in the open position as viewed from the outside of the bin.

(b) The locking system of the redesigned transfer bin in the open position as viewed from the inside of the bin.

Figure 4.18: The locking system of the redesigned transfer bin in the open position.

Chapter 5

Analysis

For the redesigned of the bin to considered successful, the design would have analysed and determined if the Functional Requirements were fulfilled using the Design Parameters specified in Section 4.1, in addition the redesigned bin would also need to outperform the SureTrack bin in the relevant categories. In order to compare the redesigned transfer bin to the original design and to gauge if it is superior to the original design, two types of analysis were performed, these analyses were constructed from the objectives in Section 4.1.1 and focus on the improvement in the structure of the bin and the possible cost savings of the improved transfer bin. In the following section a review of the design goals defined in Chapter 4 is performed and evaluated weather the design goals have been met.

5.1 Design Goals

The following is a review of the requirements and an analysis of whether, and how they were met.

5.1.1 Contain Product Batch

$FR_{1.1}$ established that the bin should be capable of containing a batch of product. The DP associated was further refined in Section 4.2.1 to state that the volume of the redesigned bin should be at least 25 litres. As indicated in Table 5.9, the volume of the redesigned bin is $25,2$ litres. Therefore the design goal of containing a product batch was achieved.

5.1.2 Support the Support System

$FR_{1.2}$ and its respective DP established that the bin should have mounting points for the support system. The redesigned bin is equipped with two welded nuts on either gable end to which the moment countering wheels of the support system are attached. Another weldnut is provided for the support pin to be screwed into the main weldment on either gable end. Therefore the design goal of providing mounting points for the support system was achieved.

5.1.3 Support the Discharge System

$FR_{1.3}$ and its respective DP established that the bin should have mounting points for the discharge system. During further refinement of this mounting the design goal of using the support pin as an attachment and rotational point for the discharge system was expressed. In the final design of the redesigned bin the support system rotates about the support pin in bushings. Additionally a welded nut is provided for a guide bar of the discharge system on the main weldment gable end. Therefore the design goal of using the support pin as mount point for the discharge system, as well as providing overall connection of the discharge system to the main weldment was achieved.

5.1.4 Decrease Risk of Fatigue Failure

$FR_{2.1}$ and the associated DP called for decreasing the risk of a fatigue failure by reducing the stress in the joint. This can be accomplished by changing the geometry of the joint between the long side and the gable end and adding a stiffener if possible. Both design elements were incorporated and as discussed in Section 5.2.1.5 the skewing resistance of the bin was dramatically increased. Therefore the design goal of increase the skewing resistance of the bin was achieved.

5.1.5 Rotate Freely During Vertical Motion

During further breakdown of the “rotate freely during vertical motion” FR it was deduced that due to the nature of the connection of the SureTrack bin to the SureTrack grader it would be necessary to maintain the current design of the end of the support pin that connects with the SureTrack grader. The geometry of the support pin end connecting to the drive system of the SureTrack grader was therefore maintained and the pin is free to rotate where it connects with the drive system. Therefore the design goal of being free to rotate during vertical motion was achieved.

5.1.6 Maintain Constant Orientation During Horizontal Motion

According to $FR_{2.3}$ the activation of the discharge mechanism would produce moment about the support pin of the bin. This moment would cause the bin to rotate unless countered. To counter this effect moment countering wheels were specified in Section 4.2.6. Moment countering wheels are a part of the design of the bin and therefore the design goal of maintaining constant orientation during horizontal motion was achieved.

5.1.7 Discharge Only When Intended

In order to fulfil $FR_{2.4}$ that stated that the bin should only discharge when intended, the DP called for a locking system to keep the bin locked during all non-discharging functions. A locking system was designed that can only open with a specific motion of the locking mechanism. Therefore the design goal of discharging only when intended was achieved.

5.1.8 Discharge In Either Horizontal Direction

As one of the customers goals with the redesign of the bin was to have the possibility of using the bin in a pure transfer system, it must be possible to discharge the bin irrespective of its travelling direction. A discharge system was designed that is fully symmetrical in respect to the direction it is activated. Therefore the design goal of discharging in either horizontal direction was achieved.

5.1.9 Promote Full Discharge

As discussed in section 4.2.9 a design goal for the discharge area of the redesigned bin was set at 60% of the SureTrack bins discharge area or $0,108m^2$. The actual discharge area of the redesigned bin is $0,125\ m^2$. Therefore the design goal of promoting full discharge was achieved.

5.2 Finite Element Analysis

In order to estimate the strength of each of the bins for comparison, basic finite element analysis (FEA) was applied to each design. The software tool used for the FEA is integrated into DSS Solidworks, the CAD design suite used by Marel Iceland, and used during the design of the redesigned bin. By using identical methods of simplification and analysis for both bins it was assumed that a fair comparison between the bin designs would result. The basic methodology applied for the analysis was to simplify the model as much as possible and to apply loads similar to those encountered by the normal operation of the bin. The case chosen for FEA analysis was the skewing loading suspected as the culprit of cracking encountered in the SureTrack bin. This analysis also serves the purpose of gauging if $FR_{2.1}$ was fulfilled.

5.2.1 Main Weldment Static Analysis

A geometrical simplification was created in order to gauge the possible increased skewing resistance of the redesigned bin in relation to the original bin. The reasoning for the selection of this test is that the possible cause of cracking in the main weldment might be due to uneven loading from the driving mechanism of the bin, causing it to skew as discussed in section 2.2.1.1.

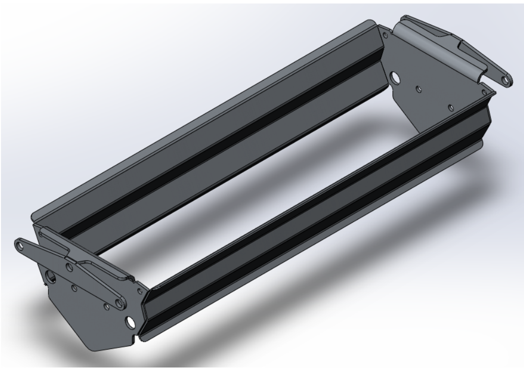
5.2.1.1 Simplified Geometry

The main weldments resistance to skewing is unrelated to the bins support system and discharge system, therefore these components can be omitted, for the same reason all weldnuts and fasteners can be omitted.

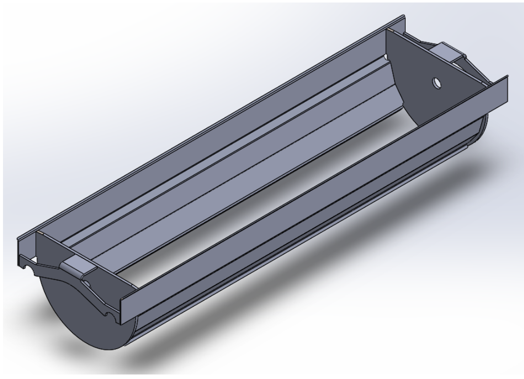
For the SureTrack bin the simplified geometry consists solely of the long sides and gable ends as shown in Figure 5.1a. In the case of the redesigned bin the simplified geometry consists of the long sides, gable ends, and braces as shown in Figure 5.1b.

5.2.1.2 Supports and Constraints

In order to affect the analysis supports are needed to constrain the model from moving in a direction not related with the analysis. To support the model during the analysis, sliding supports were added to the gable ends. These support mimic the fixation provided by the drive mechanism of the SureTrack grader where the bin is unable to move from side to side. To further support the bin, sliding supports were added to level surfaces on the top of the bin. With these support the bin is free to slide laterally as it would in the SureTrack grader, other movements are hindered without affecting the lateral motion. The constraints are pictured in Figures 5.2a and 5.2b.

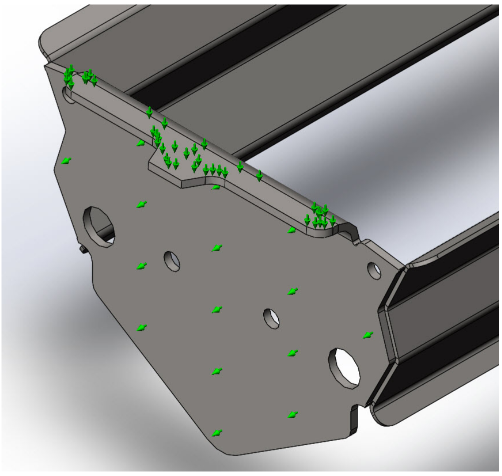


(a) SureTrack bin simplified geometry for skewing resistance analysis.

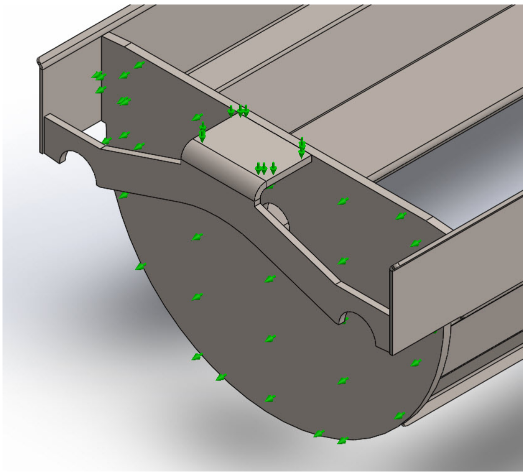


(b) Redesigned bin simplified geometry for skewing resistance analysis.

Figure 5.1: Simplified geometry for skewing resistance analysis.

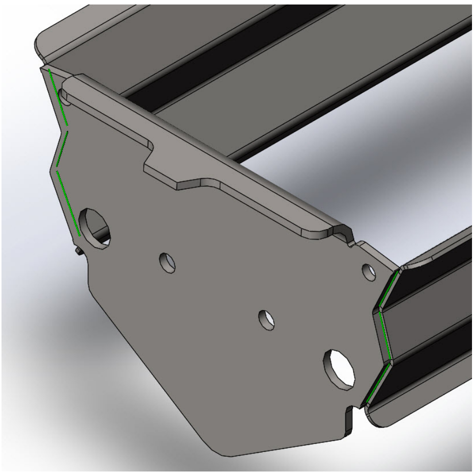


(a) Constraints placed on the SureTrack bin for analysis.

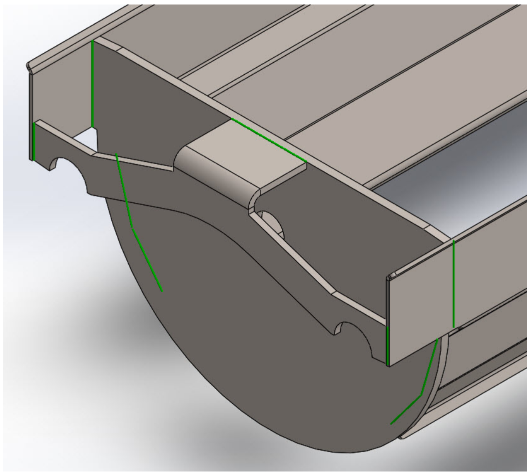


(b) Constraints placed on the redesigned bin for analysis.

Figure 5.2: Constraints placed on the bins for analysis.

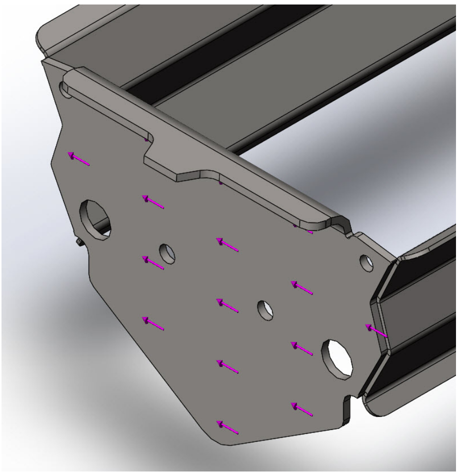


(a) Welded connections in the SureTrack bin.

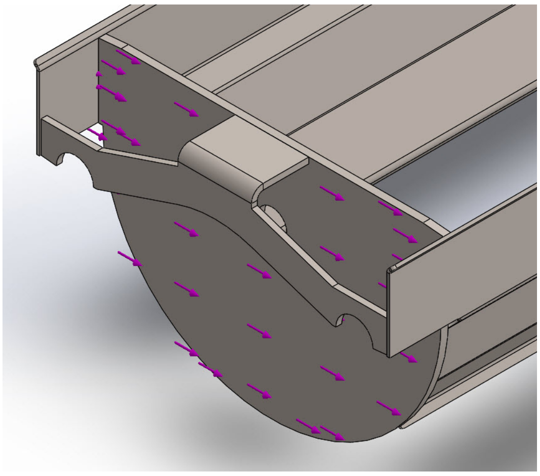


(b) Welded connections in the redesigned bin.

Figure 5.3: Bin welded connections.



(a) Loads defined for the SureTrack bin.



(b) Loads defined for the redesigned bin.

Figure 5.4: Loads placed on the bin for analysis.

5.2.1.3 Connections

The normal set of connectors defined by SolidWorks Simulation is a bonded contact set, where bodies in contact behave as if they are welded. This contact set does however not offer any analysis of the welds themselves. Therefore an edge weld connection was chosen for all contacts in the models. The edge welds were defined as having the same material properties as the base material and $2\ mm$ weld depth. the location of the welded connections are shown in Figures 5.3a and 5.3b.

5.2.1.4 Loading

For the skewing resistance analysis, equal loads acting in opposite directions were defined. The force was configured so that it was acting on the sides of the gable ends and inducing a skewing motion in the assembly. The magnitude of the force was arbitrarily chosen as $100\ N$. The configuration of the loading can be seen in Figure 5.4a for the SureTrack bin and Figure 5.4b for the redesigned bin.

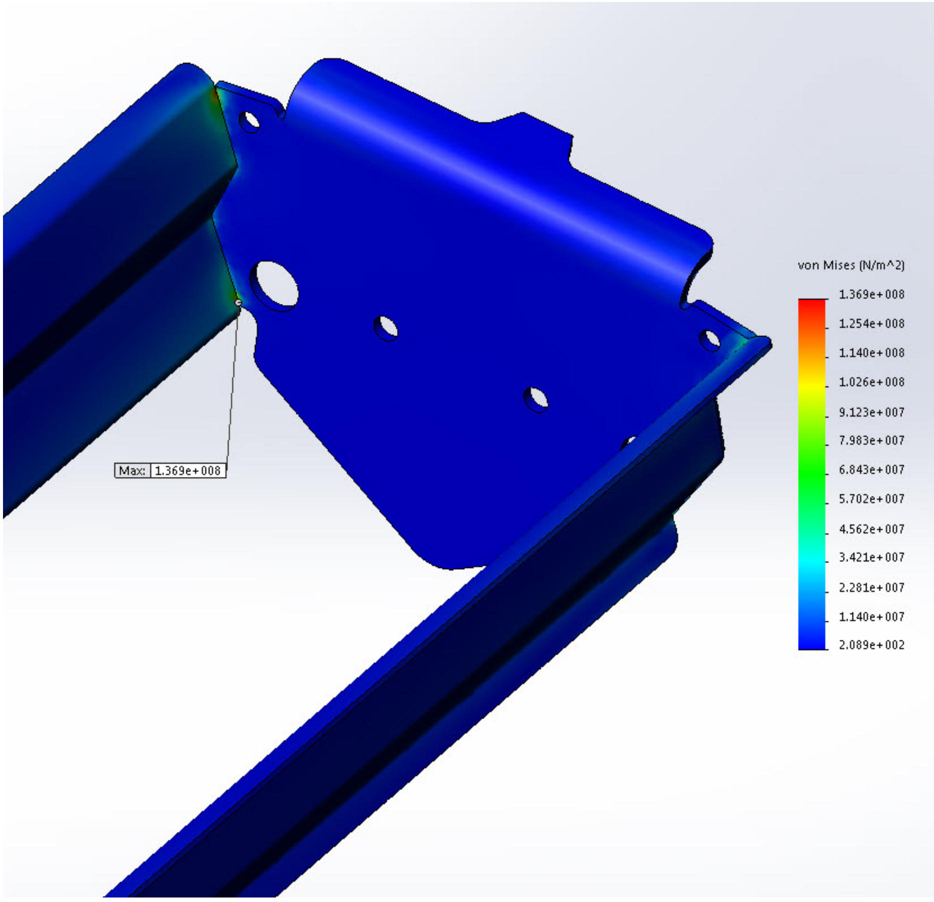


Figure 5.5: Von mises stresses in the ST bin

5.2.1.5 Results of Analysis

The results of the analysis are not surprising. The highest stresses are seen at the joint between the gable end and the long side, this is true for both designs. The stress distribution can be seen in Figures 5.5 and 5.6 for the SureTrack bin and Figures 5.7 and 5.8 for the redesigned bin.

The maximum observed stress in the SureTrack bin is $136.9\,\mathrm{MPa}$ at the top of the joint between the long side and gable end. The maximum observed stress observed in the redesigned bin is $72.2\,\mathrm{MPa}$ at the bottom of the joint between the long side and gable end. This is a decrease of $64.7\,\mathrm{MPa}$ or $47,2\%$. The stresses in the joint of the SureTrack bin indicated by the analysis are more prominent in the upper and lowermost section of the joint, they do however appear to be affecting the whole joint. The stresses also do not appear to be confined to the thinner plate as it is clearly visible that the gable end is also affected in Figure 5.6. The redesigned bin appears to fair much better in this department, as indicated in Figure 5.8 the higher values of the stresses recorded appear to be highly localised. This is presumably due to stress concentration effects near the radii where the long side departs from the gable end.

SolidWorks has the ability to check the welds themselves when the edge weld connector is defined. For both models all welds received the “ok” from the weld check tool and SolidWorks generated the weld check plots shown in Figures 5.9a and 5.9b, where a green coloured weld has this passing grade. The meaning of this is that the weld size chosen is larger than the calculated required weld size. SolidWorks also calculates the stress values at critical locations for the welds, accessing the information about the welds yields more the

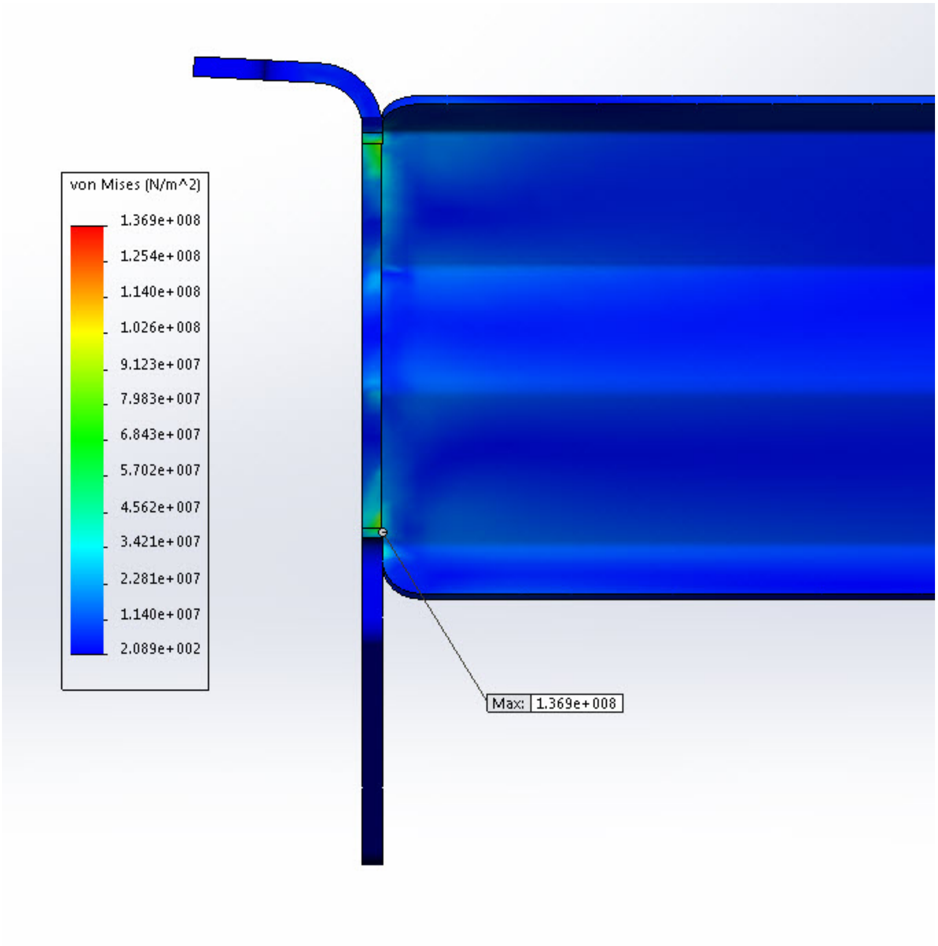


Figure 5.6: Side view of Von mises stresses in the ST bin

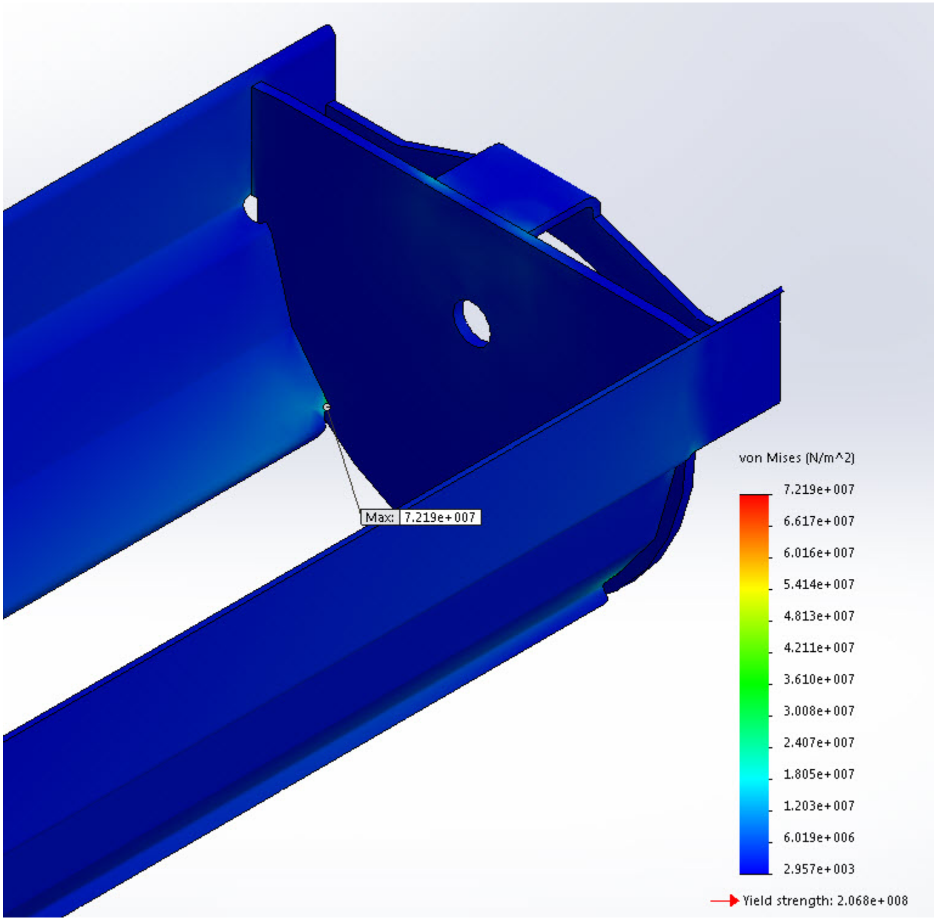


Figure 5.7: Von mises stresses in the RD bin

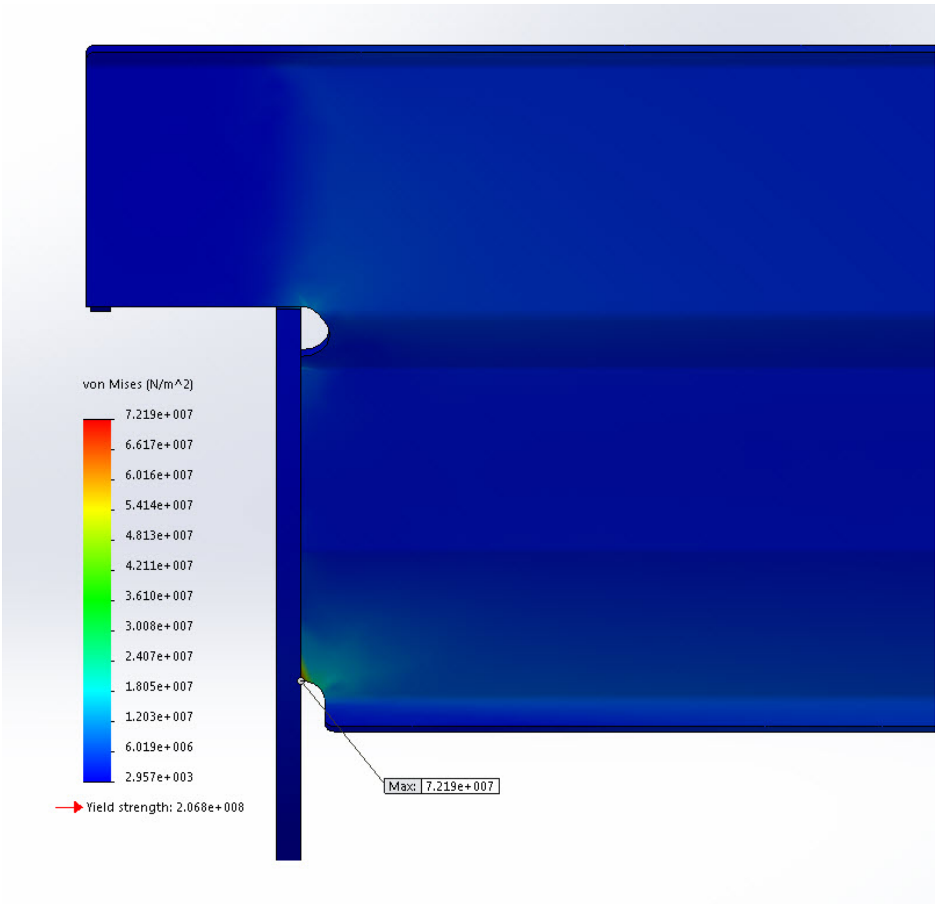
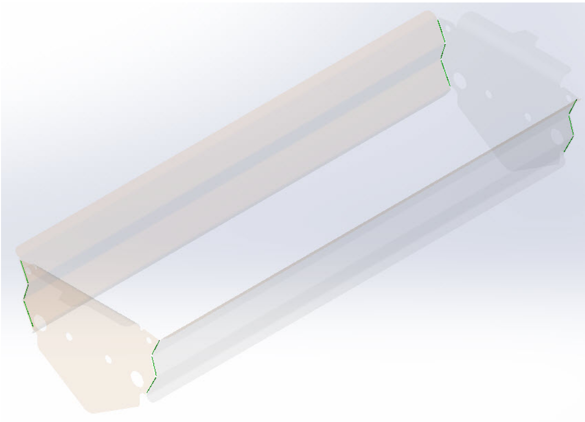


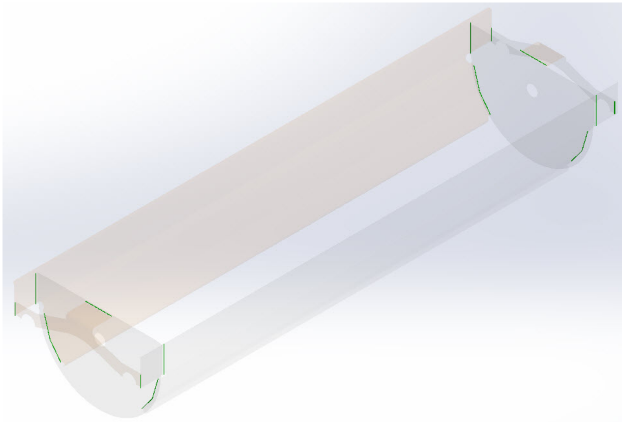
Figure 5.8: Side view of Von mises stresses in the RD bin

Table 5.1: Stresses in welds.

	SureTrack bin	**Redesigned bin**
σ perpendicular	227,88 MPa	205,04 MPa
τ perpendicular	-227,88 MPa	-205,04 MPa
τ parallel	86,95 MPa	31,12 MPa

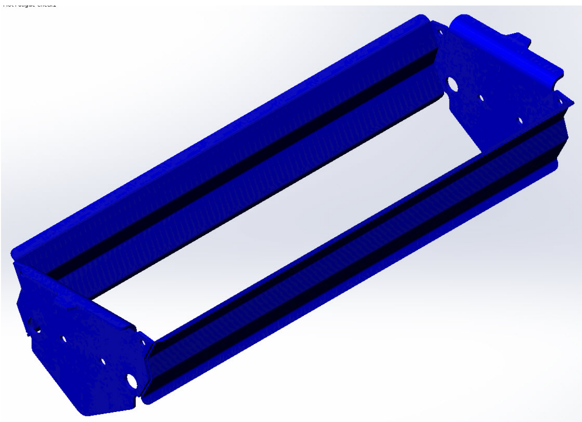


(a) Weld plot for the SureTrack bin.

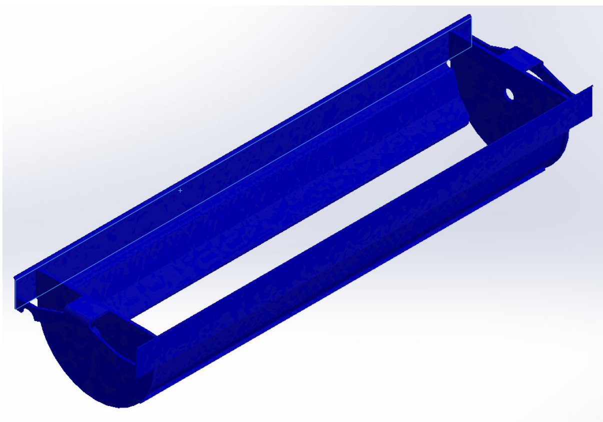


(b) Weld plot for the redesigned bin.

Figure 5.9: Weld plots for both bin designs.



(a) Fatigue check plot for the SureTrack bin.



(b) Fatigue check plot for the redesigned bin.

Figure 5.10: Fatigue check plots for both bin designs.

maximum stresses calculated by SolidWorks, these are listed in Table 5.1. While both get the “ok”, it’s clear that the stresses in the welds are lower in the redesigned bin.

A feature of SolidWorks’ static analysis is the fatigue check plot. Using the feature it is possible to estimate whether the part in question is susceptible to fatigue. This fatigue check is extremely simplified and not based on any fatigue related input from the designer. Running the analysis on both bins yielded the fatigue check plots in Figures 5.10a and ref 5.10b, for the SureTrack and the redesigned bins respectively. Both bins are entirely coloured blue in the plots, meaning that neither bin is estimated to be susceptible to fatigue failure.

5.2.2 Main Weldment Fatigue Analysis

Despite the results of the fatigue check, a more comprehensive fatigue study was carried out using the results from the static analysis of the main weldment as a loading event. This fatigue analysis was performed to confirm the results of the more basic fatigue check.

5.2.2.1 Analysis Parameters

By inserting the results from the static analysis as a loading event in to a fatigue analysis it is possible to determine the effects of repeated loading cycles using the loading conditions defined in the static analysis on the assembly.

Once the static analysis has been performed the fatigue analysis is quite simple, only the following parameters were defined.

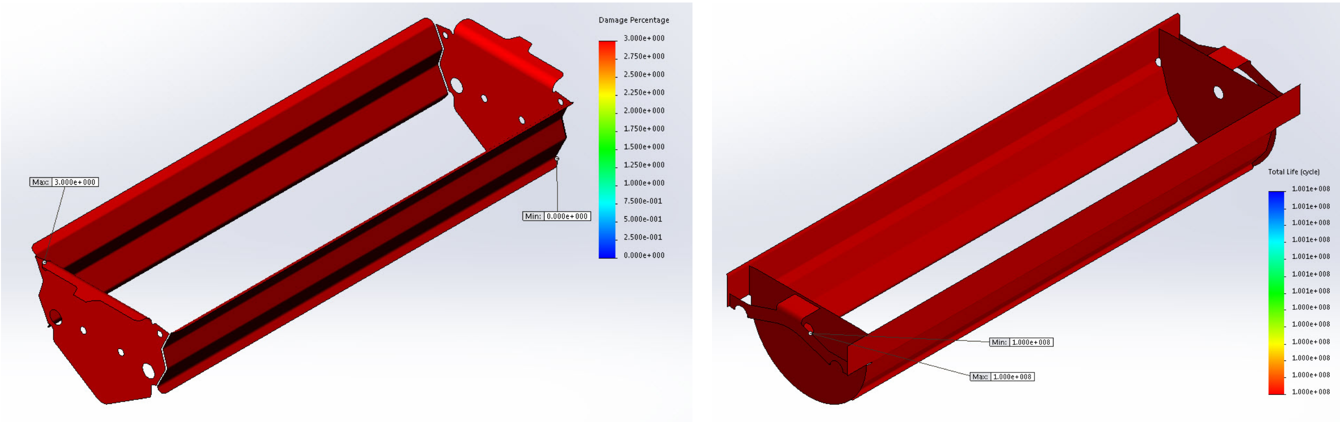
- **Number of cycles**
  For the event defined, which in this case was the repeated application of the loads defined in the static skewing analysis, the number of the load-unload cycles had to be defined. As discussed in Section 2.2.1.1 the skewing could possibly be due to the discharge mechanism of the bin being activated or oscillations in the drive system of the grader. Each of these scenarios would have wildly different number of cycles acting upon the bin. Should the fatigue loading be generated by the activation of the discharge system only a rough estimation of cycles experienced by a bin in a grader running for twelve hours per day, six days per week for a lifetime of fifteen years are around $3,37$ million. An oscillating load generated by the drive system could have happen with much higher frequency. A load generated every other second would generate just over 101 million cycles. A third scenario would be where these loads both exist, presumably with different magnitudes, and together contribute to the possible failure of the bin.

  The number of cycles was defined as 3 million.

- **Loading type**
  Two general types of loading are used in fatigue analyses. Fully reversed loading is where the stress from the load goes from zero to a positive value and back to zero, then to a an equal negative value and back to zero, and then repeats. Zero based is where the load goes from zero to full positive or negative value and back to zero, the cycle is then repeated but always in the same direction.

  For the loading of the bin fatigue analysis zero based loading was chosen as this is how the fatigue load generated by the chain drive of the SureTrack grader would affect the bin.

- **Material S-N curve**
  For SolidWorks Simulation to calculate the fatigue life of the part it needs information on the behaviour of the material when exposed to fatigue loading. Measurements of such load cases are known as S-N curves. S-N curves provide information on the number of cycles (N) a test piece can withstand at a given stress level (S). S-N curves are generated for material using tensile testing machines where the test piece is subjected to repeated loading at a certain stress level. Once the test piece fails at some number of cycles a point on the S-N graph can be plotted. This is then repeated for a number of stress levels, generating the S-N curve for the material.



(a) Damage plot for the ST bin.

(b) Damage plot for the RD bin.

Figure 5.11: Damage plot for both bin designs.

SolidWorks provides numerous S-N curves out of the box. For the fatigue analysis an S-N curve for chrome-nickel steel was used.

5.2.2.2 Analysis Results

The results of the fatigue analysis can be seen in the damage plots generated with SolidWorks for both designs in Figure 5.11 and the life cycle plot in Figure 5.12. The damage plot indicates how much of the fatigue life has been used up when the number of cycles specified in the analysis parameters have been completed. The life cycle plot estimates the total cycles needed for each element of the part to fail.

Both plots are equally unimpressive as the whole assemblies are issued with the same values by SolidWorks as a result of the analysis. According to the analysis the SureTrack bin has, in its entirety, used up 3% of it's fatigue life and has an overall estimated fatigue life of 100 million cycles. The redesigned bin appears to have used up 1% of its fatigue life after 3 million loading cycles. Interestingly SolidWorks estimates the overall fatigue life of the RD bin at the same 100 million cycles as the SureTrack bin.

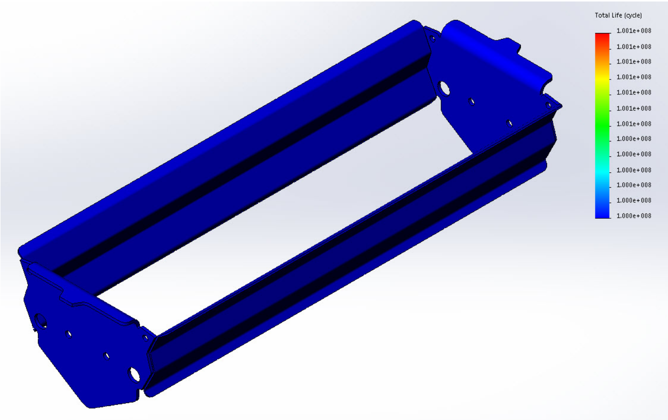
The results of the fatigue analysis confirm the results of the fatigue check analysis, the base material of neither bin is susceptible to fatigue failure. The same is not necessarily true for the welds joining the main weldment, a weld fatigue analysis is however not within the scope of the project.

5.3 Manufacturing Metrics

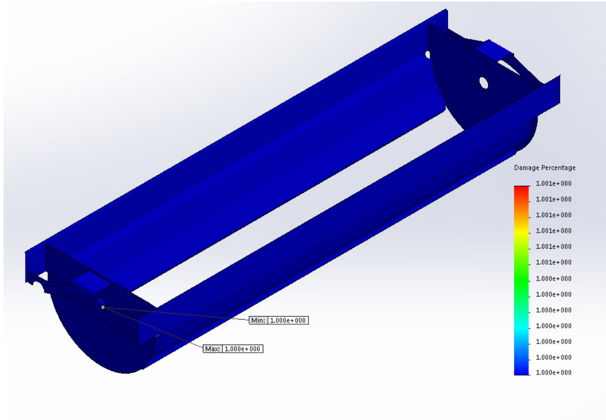
To compare how much work by each manufacturing process is required, a number of manufacturing metrics were collected on each design.

5.3.1 Welding

Two different types of data can be drawn from the models regarding the welding required on each design, the number of individual welds requiring set up and adjustment and the total length of the welds. By analysing the designs the following table for the number of individual welds is populated.



(a) Life cycle plot for the ST bin.



(b) Life cycle plot for the RD bin.

Figure 5.12: Life cycle plot for both bin designs.

Table 5.2: Number of welds required for bin construction.

Element	SureTrack bin	Redesigned bin	Diff. from ST bin
Main weldment	22	18	-4
Support system	0	0	0
Discharge system	12	14	2
Total	34	32	2

By measuring the length of each of the joints in Table 5.2 using measurement tool of Solidworks the data in Table 5.3 is compiled.

Table 5.3: Total length of welds required for bin construction.

Element	SureTrack bin	Redesigned bin	Diff. from ST bin
Main weldment	2897 mm	2902 mm	5 mm
Support system	0 mm	0 mm	0 mm
Discharge system	2456 mm	1777 mm	-679 mm
Total	5353 mm	4244 mm	-1109 mm

5.3.2 Sheet Metal

When it comes to sheet metal fabrication two metrics can be compiled on the bin design, the total length of sheet metal cutting required and the total number of bends required in the forming of parts. These metrics are chosen for they are either the most labour intensive or time intensive. Additionally three other metrics are available, the total number of cut sheet metal parts, the bend angle of each bend and the cumulative bend angle per part or per assembly. These three factors were deemed irrelevant as the processes are at this stage fully automated, the laser cutter moves very relatively quickly between cut locations in relation to the required cutting time and the time required to complete each individual bend increases only marginally as a factor of the bend angle.

Using each respective model and the measurement tool used to measure the weld length, the information in Table 5.4 on the total sheet metal cutting length is compiled. The cut length is summarised irrespective of the thickness of the sheet goods.

Table 5.4: Total length of sheet metal cuts.

Element	SureTrack bin	redesigned bin	diff. from ST bin
Main weldment	6534 mm	7663 mm	1129 mm
Support system	0 mm	889 mm	889 mm
Discharge system	7633 mm	7774 mm	141 mm
Total	14167 mm	16326 mm	2159 mm

Again using the model, the information on the number of bends and bent items is collected by counting, this information is displayed in Table 5.5 and table 5.6 respectively.

Table 5.5: Total number of sheet metal bends.

Element	SureTrack bin	redesigned bin	diff. from ST bin
Main weldment	10	12	2
Support system	0	0	0
Discharge system	6	18	12
Total	16	30	14

Table 5.6: Total number of bent sheet metal items.

Element	SureTrack bin	redesigned bin	diff. from ST bin
Main weldment	4	4	0
Support system	0	0	0
Discharge system	2	6	4
Total	6	10	4

5.3.3 Turning and Milling

Collating the number of turned and milled parts of both bins yields the figures in Table 5.7. Included in the part count for the discharge system of the redesigned bin are the four pins of the locking system. These parts however do not require a machinist nor a lathe to produce, they can simply be cut from 8 mm rod stock. However for the simplification of comparison these parts will be included with the turned and milled parts.

Table 5.7: Total number of turned and milled parts

Element	SureTrack bin	Redesigned bin	Diff. from ST bin
Main weldment	12	8	-4
Support system	4	6	2
Discharge system	22	16	-6
Total	38	30	-8

† Purchased items does not include standard bolts and washers.

5.3.4 Part Count

Drawing on the data presented in Table 2.1 in Chapter 2 and Table 4.6 in Chapter 4 and comparing the the part count of each respective design yields the following table of the change in part count from the original SureTrack bin to the redesigned locking bin.

Table 5.8: Changes in part count from SureTrack bin to redesigned bin.

Element	SureTrack bin	Redesigned bin	Diff. from ST bin
Main weldment	18	14	-4
Support system	12	16	4
Discharge system	30	34	-4
Total	50	46	-4

† Purchased items does not include standard bolts and washers.

5.3.5 Volume of the Redesigned Bin

Using Solidworks to measure the area of the container section of the bin and multiplying with the overall length of the container section yields the total volume of the bin. The volume of the redesigned bin has a total volume just over 25 litres (Table 5.9), whereas the SureTrack bin has a total volume of just under 31 litres (Table 5.9). The volume decrease is 5,6 litres or $18,2\%$.

Table 5.9: Volume of the redesigned bin.

		Redesigned bin	**SureTrack bin**
Section area	$[mm^2]$	32080	38091
Section area	$[m^2]$	0,032080	0,038091
Length	$[mm]$	785	808
Volume	$[m^3]$	0,02518	0,030778
Volume	$[l]$	25,18	30,78

5.4 Manufacturing Cost

To further estimate if the redesigned bin could be manufactured at less cost than the Sure-Track bin, Solidworks Costing was employed.

Solidworks Costing is Solidworks' integrated costing tool, and is intended to be used as part in a design for cost process where the designer can use the costing tools to quickly estimate the manufacturing cost his design or as a tool for quoting manufacturing costs to customers.

Costing does not analyse the design according to the features of the design tree but instead it analyses the geometry of the item based on how it would be manufactured. Geometry is costed differently based on the type of part is being designed. The costing tool uses standard templates to estimate total cost of manufacturing the item. The templates can be customised to each companies specific needs, it is possible to adjust to base cost of raw material, costs associated with manufacturing processes, labour costs specific to machines and processes, company specific manufacturing information such as feed rates and setup costs, the cost of custom operations such as deburring, surface treatment, anodizing, and data entry, and the cost of standard library parts [14].

When working with sheet metal parts, Costing includes the following operations in its costing estimation [15].

- Flat stock cutting (e.g. laser, waterjet, or plasma cutting)
- Library features (e.g. punching and forming)
- Bends
- Custom operations (e.g. surface treatment and heat treating)
- Machine setup (e.g. press brake setup)

When calculating the cost of machined parts, Costing includes the following [15].

- Milling (e.g. face or end milling)
- Drilling (e.g. drilling, reaming, or tapping)
- Turning (e.g. inside and outside turning or face planing)
- Library features
- Custom operations (e.g. surface treatment and heat treating)
- Machine setup (e.g. lathe or milling machine setup costs)

Costs of welded assemblies can be estimated using Costing, the following features are included in a weldment cost analysis [15].

- Weld length
- Weld type

5.4.1 Costing Analysis Set Up

In order to estimate the cost of manufacturing each bin the Costing tools had to be configured. The Costing tool has extensive configuration options allowing for the cost of each part to be calculated from multiple factors.

The cost calculations for the bins can be split up into three categories, sheet metal components, machined parts, and welding. Each of these categories needs customised settings in order to accurately estimate the manufacturing cost, additionally the cost of the raw material needs to be added.

For all conversions between US dollar and Icelandic krónur a fixed exchange rate of 130 USD/ISK was used.

5.4.1.1 Labour Costs

In order to estimate the production cost of cut and bent sheet metal stock some baseline assumptions must be made. To estimate the cost of labour in manufacturing, information from the latest release of an annual wage survey[16] conducted by the labour union for mechanics and metal workers (is. VM, Félag vélstjóra og málmtæknimanna) among its members. On page 43 the average pay per hour is listed according to education, the information is shown in Table 5.10.

Table 5.10: Hourly wages for metal workers [16].

Education	Hourly wage [ISK]
Marine engineer, class I & II	2.180
Marine engineer, class III & IV	2.447
Marine engineer, class VF	2.280
Mechanic	2.276
Machinist	2.417
Ship/pressure vessel builder	2.128
Welder	2.120

The information in Table 5.10 forms a baseline for costing parameters further defined in the following sections.

5.4.1.2 Sheet Metal Set Up and Assumptions

The following parameters need to be defined in the sheet metal costing template.

- **Cost of raw material for each thickness**
  The cost of raw materials is defined in Section 5.4.1.5. The cost was input as $500\ \frac{ISK}{kg}$ for all thicknesses.

- **Set up cost for cutting**
  The set up cost for each lot of manufacture was assumed to be equivalent to 1 hour of the laser operators time. The laser operator is assumed to be a mechanic with an hourly wage of $2.276\ \frac{ISK}{h}$, resulting in a set up cost per lot of $2.276\ ISK$.

- **Cost per unit length of cutting for each thickness**
  Based upon figures in a review by Donald Hoffman[17] the cost of laser cutting the

sheet stock was estimated. The values in Hoffman's findings were converted into ISK using the exchange rate defined in Section 5.4.1. Conversions were also affected for imperial units into metrics units. The results of the conversion is shown in Table 5.11.

Table 5.11: Sheet metal cutting costs.

Sheet thickness [mm]	Cost per unit length [ISK/mm]
2,5	0,0015
4	0,0071
5	0,0136

- **Set up cost for bending**
  The time needed for the set up of each part in the press brake and programming the machine was estimated at 5 minutes of the machine operators time per part. The machine operator is assumed to be a mechanic with an hourly wage of $2.276 \ \frac{ISK}{h}$, resulting in a set up cost per part of $189,76 \ \frac{ISK}{part}$.

- **Cost per bend for each thickness**
  Cost for each bend, including labour and machine costs were assumed to be $100 \ \frac{ISK}{bend}$

5.4.1.3 Machining Set Up and Assumptions

The following parameters need to be defined in the machining costing template.

- **Cost of raw material for each thickness**
  The cost of raw materials is defined in Section 5.4.1.5. The cost was input as $600 \ \frac{ISK}{kg}$ for cylindrical stainless steel stock and $900 \ \frac{ISK}{kg}$ for cylindrical POM stock.

- **Machine cost**
  For the machine cost the defualt value of 20 USD was converted to 2600 ISK using the exchange rate defined in Section 5.4.1.

- **Labour cost**
  The labour cost of a machinist was specified as 2.417 ISK as defined in Section 5.4.1.1.

- **Load/unload time**
  The default value for the load and unload time of 5 minutes was maintained.

- **Operation set up time**
  The default value of the operation set up time of 60 minutes was maintained.

For mill, drill, and lathe operations the Costing tool allows for the customisation of spindle speeds and feed rates for each operation, material, stock type, stock size and machine tool. All values were left at their default settings.

5.4.1.4 Welding Set Up and Assumptions

The following parameters need to be defined in the multipart costing template.

- **Machine cost**
  For the machine cost the defualt value of 5 USD was converted to 650 ISK using the exchange rate defined in Section 5.4.1.

- **Labour cost**
  The labour cost for a welder was specified as 2120 ISK as defined in Section 5.4.1.1.
- **Operation set up time**
  The default value of the operation set up time of 5 minutes was maintained.
- **Set up time distribution** With the set up time distribution parameter it is possible to select if the operation set up time is calculated once for the total quantity of items to be welded, once for a single lot of parts to be welded or once per individual item to be welded. The default setting is to calculate once per lot, this was changed to calculate the set up time to every part or assembly. As each welded assembly would require time to set up and clamp by the welder.
- **Cost per unit length of weld**
  To estimate the cost per unit length of weld a welding calculator provided by Miller Electronic was employed[18]. The calculator yields suggested welding speeds based on material being welded and thickness of the base material. The calculator is based on imperial units. Conversion yielded the values in Table 5.12

  Table 5.12: Welding speed and cost.

Base material [mm]	Weld type	Weld speed [mm/s]	Weld cost [ISK/mm]
3	Butt	4,2	2,49
6	Butt	3,4	1,99
3	Fillet	5,1	2,99
6	Fillet	4,2	2,49

  For both models butt welds were defined with a weld penetration depth of $2\ mm$, fillet welds were defined having a root depth of $2\ mm$. It is assumed that the amount of work required to complete both types of welds the same irrespective of the base material being welded. An average of $2,5\ ISK/mm$ was calculated from the values in Table 5.12 and used as the cost of welding one millimetre of each type of weld.

5.4.1.5 Raw Material Cost

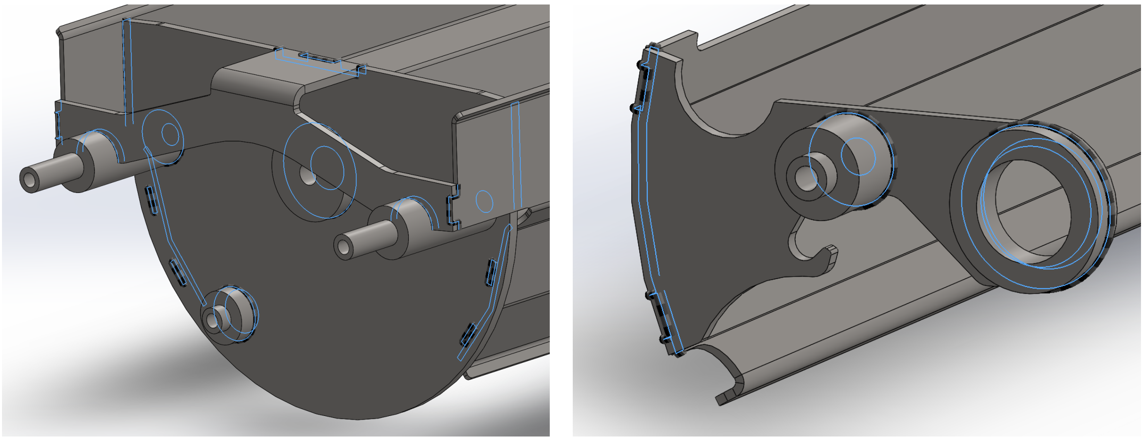
The bin is composed of two raw materials, Stainless steel 1.4301 according to EN 10088 which is identical to the steel designated as AISI 304 by the American Iron and Steel Institute, and a high stiffness thermoplastic known as Polyoxymethylene (POM).

The steel used is both in sheet and cylindrical form. The prising of each form was attained from a local company called Málmtækni. They quoted a price of $500\ \frac{ISK}{kg}$ for sheet goods and $600\ \frac{ISK}{kg}$ for cylindrical stock.

The POM used in the bins is only in cylindrical form, Málmtækni quoted a price of $900\ \frac{ISK}{kg}$ for cylindrical stock.

5.4.2 Part Configuration

After the initial configuration of the parameters used for costing were defined, each part and assembly had to be configured to allow for the costing calculation to run. Different parameters were required for parts depending on their nature as with the initial configuration.



(a) Welds defined in the main weldment of the redesigned bin.

(b) Welds defined in the discharge door of the redesigned bin.

Figure 5.13: Welds defined for weld analysis in main weldment and discharge door.

5.4.2.1 Sheet Metal Parts

For sheet metal parts material was selected as AISI 304 stainless steel. Additionally the use of sheet steel had to be defined. To define the use of sheet steel three methods are available. Firstly it possible to use the bounding box of the part as the used sheet steel. This method would be applicable to sheet steel cut using shearing methods, for a laser this is considered excessive as the machine operator arranges the items to be cut as they fit best on the sheet. Secondly it's possible to define the offset of the cut, this would be directly applicable to cutting methods such as laser, waterjet, or plamsa cutting as the cutting methods by their nature leave a cutting kerf of varying widths. This parameter was set to $1\ mm$. Thirdly the waste can be defined as a percentage of the part being cut, this parameter was set to $5\ \%$.

5.4.2.2 Machined Parts

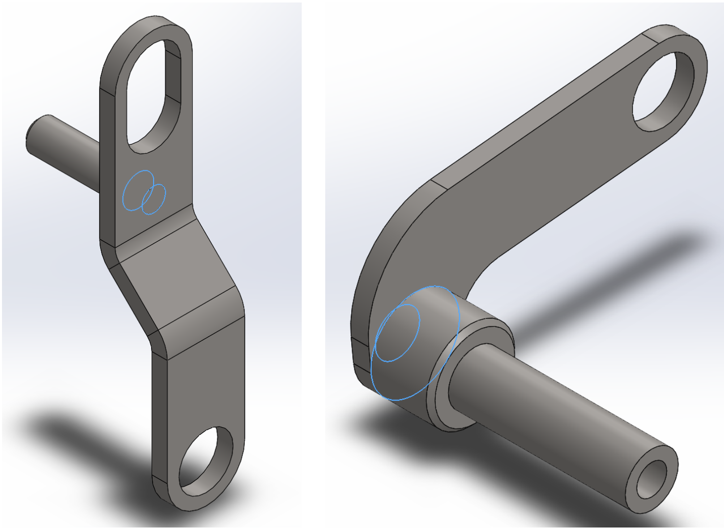
For steel machined parts material was selected as AISI 304 stainless steel. The stock body was defined as cylindrical with the diameter defined as the next size up divisible with $5\ mm$. An overlength of $10\ mm$ was added to allow for end planing.

5.4.2.3 Welded Assemblies

For the welded assemblies all welded joints were defined, all fillet welds were specified having a throat length of $2\ mm$, butt welds were defined as having a weld depth of $2\ mm$. All the welded assemblies are shown in Figures 5.13 and 5.14.

5.4.2.4 Sub Assembly Considerations

The way the SolidWorks Costing tool deals with a top level assembly is to evaluate the production cost of each individual part, a sub assembly contained within the top level assembly is therefore only evaluated as a collection of parts. Countering this shortcoming is critical, especially in the case of welded assemblies where a considerable amount of work remains



(a) Welds defined in the opening link of the redesigned bin.

(b) Welds defined in the guide link of the redesigned bin.

Figure 5.14: Welds defined for weld analysis in the opening and guide links.

once the parts have been produced. Another caveat of the Costing tool is that it is only capable of estimating the cost of welding within the welded assembly itself.

To counter these shortcomings only those parts considered to be non-welded were selected for Costing in the top level assembly.

5.4.3 Results of Costing Analysis

With the part Costing definitions complete the results from the costing analysis were available. The results of the Costing analysis are detailed in the following sections for the SureTrack bin and the redesigned bin respectively.

5.4.3.1 SureTrack Bin

As described in Section 2.2.1 the SureTrack bin is made up of 3 main elements. However due to the shortcomings described in Section 5.4.2.4, dividing the results from the costing analysis in the same way is impractical. Therefore the results are divided into components that are welded. The cost of the welded assembly includes each part that goes into creating it as well as the cost of setting up and welding the components together. The additional components that need to be attached to the welded assemblies are covered in the main assembly.

The costing analysis of the SureTrack bin is divided into the main weldment, discharge doors, lock assembly. The remainder of the parts are added in the main assembly, for the SureTrack bin these additional parts are the moment countering wheels and the POM parts of the locking system, more precisely the wheel that contacts the discharge actuation mechanism of the SureTrack grader, and the wheel that provides the end stop for the locking mechanism. The main weldment is composed of the greatest number of parts and has the greatest number and length of welds, this is reflected in the parts and welding costs.

Table 5.13: Costing results for the SureTrack bin.

Component	Part cost	Welding set up cost	Weld cost	Total
Main weldment	16 296,9	230,8	7 410,0	23 937,8
Discharge door	3 057,8	230,8	2 115,9	5 404,6
Lock assembly	4 079,2	230,8	981,0	4 078,8
Main assembly	5 327,4	0†	0†	5327,4
Total	27 549,1	692,4	10 506,9	38 748,6

† No welding is required for the main assembly.

5.4.3.2 Redesigned Bin

Like the SureTrack bin, the redesigned bin is also made up of three main elements as described in Section 4.3.1, however as with the SureTrack bin, the same restrictions discussed in Section 5.4.2.4 apply. Therefore the redesigned bin is divided in a similar manner to the SureTrack bin.

The costing analysis of the redesigned bin is divided into the main weldment, discharge door, opening link, and guide link. The parts not included in the aforementioned sub assemblies are covered in main assembly, these parts are the moment countering wheels and the wheels of the discharge system.

Table 5.14: Costing results for the redesigned bin.

Component	Part cost	Welding set up cost	Weld cost	Total
Main weldment	13 533,9	230,8	6 931,6	20 696,4
Discharge door	3 803,8	230,8	2 982,3	7 016,9
Opening link	443,6	230,8	109,5	783,9
Guide link	1 352,0	230,8	234,7	1 817,5
Main assembly	7 118,6	0†	0†	7 118,6
Total	26 251,9	923,2	10 258,1	37 433,3

† No welding is required for the main assembly.

5.4.4 Purchased Parts

Both bin designs contain purchased parts that are not included in the costing analysis generated by SolidWorks' Costing tool. The purchased parts are bolts, washers and bushings as indicated in Table 5.15 the number of bolts and washers is equal in both design resulting in the same net cost for these items. The redesigned bin, due to the change in the discharge system needs one more pair of bushings to function. It does however completely do away with the rather costly rod ends and speciality bolts altogether, as well as the threaded rods and jam nuts required to make the connection between the rod ends.

Table 5.15: Purchased parts for both bin designs.

Component	SureTrack bin	Redesigned bin
Bolts	12	12
Threaded rod	4	0
Washers	8	8
Jam nuts	8	0
IGUS bushings	20	22
IGUS rod ends	8	0
IGUS rod end bolts	8	0

The IGUS rod ends used in the SureTrack bin are made of plastic and require a special bolt for the bearing end of the rod end. The cost of the IGUS rod ends is estimated at 500 ISK each, including the special bolt. The total cost of the rod ends and bolts for a single bin totals at 4000 ISK, the cost of the jam nuts and threaded rod is omitted. Adding the cost of the rod ends, yields a final cost of 42748,6 ISK for the SureTrack bin and a total cost decrease of 12,4%.

Chapter 6

Conclusions and Discussion

6.1 Discussion

The design of the redesigned (RD) bin appears promising according to the analysis of Chapter 5. These analysis are however only approximations of real world performance and do not replace prototype and model testing of the bin. From the models and analyses it's impossible to gauge the behaviour of the RD bin during various operations such as transition from vertical to horizontal motion and vice versa, coming into contact with the discharge actuation mechanism of the grader, and the behaviour of the discharge mechanism during motion. The practicality of a discharge system that works against the force of gravity needs to be investigated further. Would such a system perhaps induce excessive forces in discharge actuation mechanism of the grader causing structural problems to migrate from the bin to the actuation system. From the results of the analyses it's safe to conclude that further investigation into the feasibility of this design is warranted.

Another matter concerning the activation of the discharge system of the bin against gravity is the speed with which the system can be activated. The accuracy of the discharge of the bin is directly related with how quickly it can be discharged. In the case of the SureTrack bin the opening of the discharge doors is accomplished by the weight of the doors themselves and the fish contained in the bin, the product begins to move out of the bin nearly immediately upon activation of the system. For the RD bin it would have to be investigated at what point in the discharge cycle the ejection of the product would begin as the discharge doors would have to be moved some minimum of degrees for the discharge doors to separate sufficiently to allow product to pass.

The objectives of this thesis were as stated in Section 1.1:

- Evaluate an appropriate design framework.
- Design a replacement bin for the SureTrack grader using the selected framework.
- Evaluate the feasibility of the design.

During the course of this thesis project all of these objectives have systematically been discussed, addressed, and finished. In Chapter 3 an evaluation of the Axiomatic Design framework was performed and it's features discussed. In Chapter 4 the design of the RD bin was performed using the AD framework. Lastly the feasibility of the design of the RD bin in relation to the SureTrack bin was evaluated in Chapter 5, and further discussed in Section 6.2 in this chapter.

The SolidWorks Costing tool can be an invaluable design tool when set up correctly, especially when actual data can be collected from the manufacturing departments and used to calculate the cost of each operation defined in the costing templates. However the results from the costing analysis is only an approximation of the actual cost of manufacturing the item in question. Two caveats become evident when working with the Costing tool. One is that the cost of assembly is not clear, the costing templates have provisions for per unit costing of various metrics such as welding, cutting, milling, turning, drilling, and various other operations. The actual assembly of the product is not included. Another limitation that became apparent concerns the set up of welding operations. In SolidWorks Costing welding is priced using cost per unit length of weld and the cost of setting up the welding operation. For the set up cost it is possible to select from three types of set up cost calculations as discussed in Section 5.4.1.4, where the time configured for the set up time is attributed for the entire production run, a lot of products or each product. For manual welding operations such as the ones performed on the bins each part requires setting up before welding can commence. However no distinction is made if the part requires multiple set ups because of multiple of complex welds or of it the part has a single weld. Therefore as seen in Table 5.14, the cost of set up is identical for the relatively simple opening and guide links as it is for the entire main weldment with its multiple welds and complex set up.

6.2 Conclusions

The Axiomatic Design framework proved to be an excellent method with which to systematically approach the redesign of the SureTrack bin. AD allowed for addressing each important design parameter with analysis before any work took place minimising the possibility of having to repeatedly address features as design changes were made. Defining acceptable parameters for each functional value beforehand was helpful in order to ascertain when then design was acceptable.

Designing the bin in a CAD system such as was employed in the design of the SureTrack bin and the redesigned bin proves invaluable when it comes to estimating and evaluating the design. Using two powerful software add ons included as part of the CAD suite it was possible to evaluate the strength of the RD bin versus the ST bin, as well as evaluate the manufacturing cost of each bin.

One of the primary factors for redesigning the bin was the cracking experienced in the seams between the long sides and gable ends of the bin, it was theorised that the cracking could be due to loads generated by the SureTrack grader causing the bin to skew. An analysis was designed to estimate the improvement in the redesigned bins improved ability to counter this skewing. The results from the analysis are promising. The skewing strength of the bin is improved $47,2\%$ over the SureTrack bin. As the sheet thickness's and weld parameters in the RD bin are equal to those in the ST bin the improvement is due to the geometry of the joint between the long sides and gable ends as was set out to accomplish at the beginning of the design.

According to the fatigue check analysis and the more extensive fatigue analysis the base material of neither bin appear to be susceptible to fatigue failure. The tools available in SolidWorks do not perform fatigue analysis for the weld bead itself, however the parallel shear stresses recorded in the weld bead decreased by 64% meaning that the joint strength has been increased substantially and the potential life of the part has been increased accordingly.

A second primary factor triggering the investigation into the improvement of the bin was the cost of manufacture. The ST bin is considered quite expensive to manufacture and any decrease in cost would impact the overall cost of the SureTrack grader as it is equipped with 120 bins in its standard configuration.

An analysis performed on manufacturing metrics, that is the amount of sheet metal cutting and bending, turning and milling, and welding, required to produce each design yielded interesting results as indicated in Table 6.1.

Table 6.1: Difference in manufacturing metrics between the ST bin and the RD bin.

Element	Diff. from ST bin
Sheet metal, cutting length	15,2%
Sheet metal, number of bent parts	66,6%
Sheet metal, number of bends	87,5%
Turned and milled parts	-26,6%
Welding, number of welds	5,9%
Welding, length of welds	-20,7%

The redesigned bin makes more use of manufacturing methods that are cheaper, by decreasing the need for turned and milled items and decreasing the amount of welding necessary the cost of the bin is decreased.

By focusing on using less expensive manufacturing techniques as well as eliminating the need for the rather expensive rod ends in the ST bin design the cost was decreased as shown by the costing analysis using the Costing add on for SolidWorks. According to the costing analysis the manufacturing cost of the RD bin was decreased 1315,19 ISK over the ST bin, from 38748,6 ISK to 37433,41 ISK. This amounts to a cost decrease of around 3,4 %. However, this is does not do complete justice to the savings offered by the revised design as the costing analysis was not configured to consider the cost of the rod ends of the SureTrack bin discharge system. By manually including the costs of the rod ends the savings become considerable.

When the cost of the rod ends as evaluated in Section 5.4.4 is added to the cost of the SureTrack bin, the estimated manufacturing cost totals 42748,6 ISK and the decrease in cost using the redesigned bin becomes 12,4%.

6.3 Future Work

In order for the redesigned bin to become a viable option as a replacement for the SureTrack bin further work must be done on the design. Firstly it is necessary to design a discharge actuation system that fits the SureTrack grader and is capable of activating the discharge mechanism of the redesigned bin. Secondly a more in depth analysis of the weld joining the long sides to the gable ends appear to be in order. Thirdly a prototype of the bin would have to be constructed to evaluate the workings of the discharge and discharge actuation systems, as well as the feasibility of the design. The production of prototypes could be used to further verify the findings of the project by closely monitoring the labour required for the manufacture and assembly of the bin. Based upon these findings, an improved design comes closer to production and deployment.

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